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DECARBONISATION OF TRANSPORT THROUGH ELECTRIFICATION AND SYNTHETIC FUELS

Summary of the Doctoral Thesis

RTU Press
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RIGA TECHNICAL UNIVERSITY
Faculty of Natural Sciences and Technology
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Summary of the Doctoral Thesis

Scientific supervisor
Professor Dr. sc. ing.
GATIS BAŽBAUERS

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on December 19, 2024, at the Faculty of Natural Sciences and Technology of Riga Technical University, 12/1 Āzenes Street, Room 607.

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DECLARATION OF ACADEMIC INTEGRITY

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

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Gunārs Valdmanis __________ (signature)
Date: 20.11.2024.

The Doctoral Thesis is written in Latvian. It contains an introduction, three chapters, conclusions, 50 figures, 16 tables, and nine appendices; the total number of pages is 143, not including appendices. The Bibliography contains 140 titles.

TABLE OF CONTENTS

INTRODUCTION

The European Union's (EU) energy and climate policy has been high on the EU's agenda in recent decades. While EU Member States are striving to implement the objectives and rules set out in EU-level documents, new legislative proposals are still coming up, and Member States need to develop new policy proposals to meet the common EU plans, including reducing greenhouse gas (GHG) emissions, as well as other environmental pollution related to the use of energy resources [1]

The aim of the Doctoral Thesis is to explore possible solutions for the decarbonisation of light and heavy transport (including maritime transport and aviation) based on electricity produced from renewable energy sources, assessing their technical and economic potential.

The relevance of the study stems not only from the EU's climate targets but also from rising energy prices in 2021/2022, which have encouraged many electricity consumers to switch to electricity production for self-consumption and have generally strengthened the competitiveness of renewable energy technologies also at the commercial level. In view of the various technological developments and the constraints associated with those developments, it is justified to consider both electrification, which can be called primary electrification of transport, that is to say, scenarios involving the application of electric propulsion in transport, and electrification, which can be described as secondary electrification, that is to say, technologies in which electricity is used as a resource for the production of gaseous or liquid synthetic fuels from renewable raw materials.

To achieve the goal of the Doctoral Thesis, the following tasks were set:

1. Evaluate solutions for the electrification of light and heavy transport by analysing technological and economic aspects, as well as the impact on the climate, and evaluate the dynamics of the growth of the number of electric vehicles (EVs) in the light road transport sector depending on their technological development and support instruments, as well as the impact of this dynamic on CO_2 emissions.
2. Analyse the potential impact of light EV development on the electrical load profile for various charging infrastructure development scenarios, as well as the impact on the technical-economic indicators of the electrical network.

3. Determine the potential for the use of electricity produced by photovoltaic (PV) and wind power plants (WPPs) in the light EV sector.
4. Assess the economic and technical perspectives for the decarbonisation of heavy transport through synthetic fuels produced from renewable electricity sources, taking into account the expected electrical capacity of renewable energy technologies as well as the development of synthetic fuel production capacities, technological feasibility of infrastructure and institutional aspects.
5. Evaluate the possible development trends of the electricity market price because of the increase in the electricity produced by WPPs, thus characterising the possible economic profitability and impact of primary and secondary electrification on the operation of the electricity market.
6. Offer proposals for new transport electrification policy measures and methodology for their evaluation, which may be used in the energy policy planning documents of Latvia, including the National Energy and Climate Plan, concurrently providing quantitative assumptions regarding the impact of these measures.

The hypothesis put forward: **By implementing appropriate policy measures to promote the development of electricity produced from renewable energy resources and synthetic fuels, the decarbonisation of light and heavy road transport will be possible in Latvia by 2050 through electrification of light transport and synthetic fuels in the heavy transport sector.**

Scientific significance of the Doctoral Thesis

The research is of scientific importance as it comprehensively and systematically analyses the most technologically relevant transport and electricity policy measures, covering technologies that can be used in all transport sectors. The scientific significance of the Thesis is also justified by the circumstance that it has been implemented through complementary, different methodological approaches, coming down to the final theory-based approach to integrate all parts of the study.

The joint study is based on several methodologies for evaluating electricity and transport policies from different angles. The following research methods were used in the Doctoral Thesis: system dynamics model, mathematical and statistical analysis, simulation of the operation of the energy system, and technical-economic calculations. The system dynamics model has been used primarily in the study to assess the causal relationships and interactions of different policy measures and developments over time. The energy system simulation tool has been used with the aim of predicting the impact of transport electrification measures on the technological and economic indicators of the electricity system. Mathematical and statistical analysis has been used to make calculations of the cost of electromobility per final customer, as well as historical trends in the correlation between renewable energy production volumes and wholesale prices, on the basis of which the expected dynamics of electricity price fluctuations in the future and the influence of additional sources of demand on price formation can be predicted. The technical-economic analysis has been used to compare, firstly, the costs and benefits of electricity users depending on the use of renewable energy production facilities and electric vehicles to meet mobility and energy supply needs, and secondly, to carry out the predictable dynamics of the costs of the electricity distribution system depending on fluctuations in the load on the network.

Practical significance of the Doctoral Thesis

The practical significance of the Doctoral Thesis is justified by the assessment provided by the Thesis on the sustainability of several transport electrification and synthetic fuel technologies in the conditions of Latvia, concurrently also considering the restrictions imposed by the operation of the Latvian electricity transmission system, the predictable capacity of the infrastructure, the economic justification and sustainability of electricity market prices. The study also predicts the impact of expected costs at the end-user level. As part of the study, a practical research model has been developed that can be used as a tool to assess the cost, impact on emissions and impact on the overall balance of energy supply of several synthetic fuels and electrification technologies produced by electricity. An important research aspect of the work is also the fact that the work assesses not only the possible dynamics of the implementation of policy measures over time but also the necessary institutional factors that may have an impact on the success and speed of the implementation of policy measures. The study has a direct use for improving the policy of Latvia in the electricity and transport sectors, not only to promote the achievement of the existing climate goals but also to set new, more ambitious goals, promoting the development and sustainability of both the transport and electricity sectors.

Approbation of the results of the study

The results of the study have been presented at nine international scientific conferences and in eight scientific articles (six articles are indexed in the SCOPUS database, and two articles have been submitted for review.

Publications

1. **G. Valdmanis, G, Bažbauers, "Application of EnergyPLAN Modelling Tool for comparative Analysis of Selected Energy Policies in Case of Latvia** (2019) IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON);https://doi.org/10.1109/RTUCON48111.2019.898233.
2. **G. Valdmanis, G, Bažbauers, R. Vītols, ""Impact of Electric Vehicle Charging Infrastructure on the Electric Load Profile of Power System: The Case of Latvia"** (2023) CONECT 2023: XVI International Scientific Conference of Environmental and Climate Technologies: Book of Abstracts 2023; https://doi.org/10.7250/conect.2023.041.
3. **G. Valdmanis, G, Bažbauers, M.Drobins, "Use of Synthetic Fuels Derived from Green Hydrogen and CO2 in Heavy-duty and Long-range Transport: The Case of Latvia"** (2023) CONECT International Scientific Conference of Environmental and Climate Technologies May 2023; https://doi.org/10.7250/CONECT.2023.053.
4. **G. Valdmanis, G. Bažbauers, M. Bataitis, G Bohvalovs, J. Lilo, A. Blumberga, D. Blumberga "CO2-to-Fuel – Business and Institutional Aspects of Implementation Dynamics"** (2022) Environmental and Climate Technologies 2022, vol. 26, no. 1, pp. 1182–1195; https://doi.org/10.2478/rtuect-2022-0089.
5. **G. Valdmanis, G. Bažbauers, M. Rieksta, I. Luksta, "Solar Energy Based Charging for Electric Vehicles at Fuel Stations"** (2022) Environmental and Climate Technologies Volume 26 (2022): Issue 1 (January 2022); https://doi.org/10.2478/rtuect-2022-0088.
6. **G. Valdmanis, G. Bažbauers, "Relation between Electric Vehicles and Operation Performance of Power Grid" (**2021) Environmental And Climate

Technologies Volume 25 (2021): Issue 1 (January 2021); https://doi.org/10.2478/rtuect-2021-0086.

7. G. Valdmanis, G. Bažbauers, "Synergy between Solar Energy and Electric Transport" (2021) 2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON); https://doi.org/10.2478/rtuect-2022-0088.

8. G. Valdmanis, G. Bažbauers, Influence of Wind Power Production on Electricity Market Price (2020) Environmental and Climate Technologies 2020, vol. 24, no. 1, pp. 472–482; https://doi.org/10.2478/rtuect-2020-0029.

Presentations at scientific conferences

- **Application of EnergyPLAN Modelling Tool for comparative Analysis of Selected Energy Policies in Case of Latvia.** Presentation at the IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 2019.
- **Influence of Wind Power Production on Electricity Market Price.** Presentation at the CONECT 2020: International Scientific Conference of Environmental and Climate Technologies.
- **Synergy Between Solar Energy and Electric Transport**; Presentation at the IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 2012.
- **Impact of Electric Vehicle Charging Infrastructure on the Electric Load Profile of Power System: The Case of Latvia.** Presentation at the conferenceCONECT 2023: International Scientific Conference of Environmental and Climate Technologies.
- **Use of Synthetic Fuels Derived from Green Hydrogen and CO2 in Heavy-duty and Long-range Transport: the Case of Latvia**; Presentation at the CONECT 2023: International Scientific Conference of Environmental and Climate Technologies.

- **Role of Institutional Capacity in Green Energy Transition. Gunārs Valdmanis, Gatis Bažbauers,** Presentation at the 2nd European Culture and Technology Lab+ Annual Conference, Technological University Dublin, 2023.

Structure and description of the Doctoral Thesis

The Thesis is based on thematically related eight scientific articles published or submitted to international scientific journals, six of them indexed in the SCOPUS database and freely available, as well as the presentation of six studies at an international scientific conferences. Seven articles analyse the different aspects of the decarbonisation of transport and the production and consumption of renewable energy, and one article provides an insight into the impact of institutional and economic aspects on the dynamics of the implementation of transport and energy decarbonisation measures. The Thesis contains an introduction, three chapters and conclusions:

- **A review of previously conducted studies.**
- **Research methodologies.**
- **Results and discussion.**
- **Conclusions and recommendations.**

The introduction provides the purpose of the Doctoral Thesis, followed by tasks to achieve the goal. The introduction also gives a hypothesis and describes the scientific and practical significance of the Thesis. This is followed by information on the approbation of research results through participation in international scientific conferences and published scientific articles. The review of previous research in Chapter 1 consists of an overview of the field of research, i.e. the decarbonisation of renewable energy and transport, and the relevant policy measures discussed in the author's publications. Chapter 2 describes the methodology that was used in all publications to evaluate the various technological measures for the decarbonisation of transport and the introduction of renewable energy, which are assessed as prospective in the Latvian energy and transport policy. Chapter 3 presents the results of the study based on the above methodology, which allows the author to complete the Doctoral Thesis with conclusions. The structure of the research of the Doctoral Thesis is shown in Fig. 1, reflecting, first, the goals evaluated in the Thesis, the studies that are solved during research, and the scientific publications of the author related to their execution.

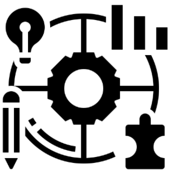
Transport sector	Methods	Results
		
• Light transport • Freight land transport • Maritime transport • Air transport	• System dynamics modelling • Technical-economic analysis • Statistical analysis • Simulation modelling of energy systems	• Carbon reduction potential in transport has been confirmed • The impact of electric transport on the operation of infrastructure and production plants has been assessed • Conformity assessment of energy production volumes and transport consumption has been carried out • Synthetic fuel production volumes have been assessed

Fig. 1. The structure of the Thesis.

1. OVERVIEW OF PREVIOUS RESEARCH

During the development of the Doctoral Thesis, the following key aspects of the research were identified when assessing the available technologies that can be used to reduce direct (emitted by vehicle exhaust) and indirect (emissions from the production process of vehicles and fuels) generated by transport.

First, the most promising technology for the decarbonisation of light passenger transport can be considered electric car technology, which is based on electricity battery and electric motor technologies (IEA (2024), Global EV Outlook 2024, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2024, License: CC BY 4.0). This is mainly due to aspects such as the expected intensity of use of vehicles, the expected frequency of use of the recharging service by users, as well as the cost advantages over the long-term running over the long-term running costs of internal combustion engine vehicles.

Secondly, the studies carried out during the development of the Doctoral Thesis also look at the most promising technologies for the decarbonisation of heavy goods and passenger land transport, as well as maritime transport, and, on the basis of the technological and operational characteristics of this transport sector, which may be considered to be synthetic fuels produced from renewable electricity sources, that is to say, fuels whose primary raw material is electricity and which are produced using hydrolysis hydrogen and carbon dioxide (CO_2).

Thirdly, the study also focuses on aspects related to the reduction of indirect emissions from the transport sector. Among other things, the study also addresses the expected trajectory of the development of renewable energy technologies in the power generation sector, since it is the generation technologies of the electricity sector that will also determine the dynamics of the reduction of transport emissions. The study also looks at the indirect and direct impact of the transport sector on electricity supply infrastructure and on the cost of using it. The work also assesses the potential of the transport sector to improve the overall economic and technical functioning of the electricity market by promoting opportunities for the successful integration of RES electricity into the electricity market, which is characterised by variable and volatile development.

Fourthly, an assessment has also been made of the feasibility of developing RES electricity production in an amount that covers the foreseeable demand for electricity, including the expected demand in the transport sector. In addition, the study set the objective of identifying the overall impact of renewables, energy-saving measures and flexibility solutions on the performance and costs of the national energy system, as well as on the level of carbon emissions from the energy sector. The study also compares five different scenarios for the development of energy policy with targets for renewable energy and flexibility technologies, as well as for energy performance indicators for buildings, which were developed for the period 2017–2050.

1.1. Dynamics of growth in the number of light EVs and changes in CO_2 emissions depending on their technological development and supporting instruments

Unlike fossil fuel vehicles (FV), the costs of EVs associated with the installation and use of infrastructure account for a very significant part of the end-use costs. Therefore, many previous studies affecting the development of electromobility have focused on tasks related to the economic and technical optimization of EV charging infrastructure, as well as the integration of electricity produced by EVs and PV. A study carried out in Portugal on the integration of park-and-ride infrastructure with PV production and EV charging services confirmed that the expected period of initial return on investment in 2017 reached around 14 years, thus confirming the feasibility of such a business model [4]. Such confirmatory results can also be attributed to a scenario where the PV and EV charging service is used in synergy with gas stations, providing the charging operator with additional income from the retail business. The studies also highlight significant advantages in terms of EV charging and PV synergy from the perspective of fluctuations in network load [5], [6]. They find that, through an appropriate pricing policy for charging services, there is great potential to reduce the need for grid use and energy storage facilities, which additionally reduces the overall emissions of EVs over their life cycle. Studies have shown that, given the current general prevalence of EVs in the transport system and the difference in the purchase prices of FV and EVs, public subsidies for their faster development are desirable for public charging services [4], [7], [7].

As a possible significant economic and technological constraint on the possible development of EVs, the investments necessary for the development of the electricity grid are mentioned, which may be caused by an increase in demand for electricity grids. However, if the load on the network infrastructure is low and sufficient to meet the demand related to the transport sector, the impact of EVs on the economic and technical functioning of the network in relation to more efficient load on the network can also be positive: by loading the network more efficiently and by making more intensive use of EV chargers, the associated EV costs will be reduced. In addition, electrification measures can also have a positive impact on PV competitiveness since, for example, the installation of PV equipment in EV charging stations allows the electricity produced by PV to be sold to the final customer, reducing the need to transfer the generated electricity to the grid.

As an increasing number of policymakers take steps to facilitate the use of EVs, it becomes more important to use available policy tools to achieve the greatest reduction in carbon emissions while ensuring the greatest availability of mobility services to the public. Mathematical modelling of the synergy of charging PV and EVs has been studied by many researchers. However, in most cases, modelling was carried out with a focus on the economic perspective [8] or the network operating perspective [7]. At the same time, when assessing the environmental impact aspects of synergies, the researchers point out that the use of a similar business model in different geographical regions can lead to significantly different results; for example, in European countries, the positive impact of such synergies may be greater than in many other regions [9]. Therefore, it can be argued that to obtain the best results, it is necessary to make a comparison of different EV promotion tools for a particular country or region, using specific parameters that characterize the differences in transport use within the country, differences in the efficiency of PV equipment, etc. This study uses economic parameters and technical assumptions that characterize countries or regions such as Latvia, but the developed system dynamics model, with the necessary adjustments, can also be used to analyse other countries or regions.

1.2. Impact of light EV charging infrastructure development scenarios on the electrical load profile in electricity grids on their efficiency

A hidden obstacle to the electrification of transport is that there is public confusion about the impact of electrification on total electricity costs, infrastructure and production costs [10]. The demand for EV charging can significantly change the load profile of the energy system [11], which, when combined with variable-design power generation sources such as wind power plants (WPPs) or PV, can create demand for new infrastructure. In order to safely plan the development of electricity grids and EV charging infrastructure, appropriate modelling of different scenarios for the development of the energy system needs to be carried out. Previous studies confirm that one of the modelling tools that can be successfully adapted to such analysis is the EnergyPLAN modelling tool [12]. The purpose of this study is to use the EnergyPLAN modelling tool to assess the impact of EV charging on the electrical load profile depending on two key factors – firstly, the number of EVs, and secondly, the operational characteristics of the charging infrastructure, depending on the extent to which the charging infrastructure provides fast, medium-fast or slow charging. In addition, the study assesses how much of the total energy demand for EVs can be met by renewables, i.e. wind and PV energy. A comparison of previous studies confirms that EnergyPLAN can be rated as a highly adaptable and flexible energy planning tool that can be used both for modelling larger and integrated energy systems [15], [16] and for smaller and isolated energy systems such as islands or smaller regions [16], [17]. The tool has been successfully used both to compare different energy policy scenarios [7] and to assess the efficiency of different flexibility technologies, such as energy storage [19]–[23], or the potential of renewables to replace primary sources of supply and fossil fuel energy sources in national energy systems [24], [25].

1.3. The potential for the use of electricity produced by solar and wind power plants in the light EV sector

Mathematical modelling of the synergy of solar energy and EV charging has been done by many researchers. However, in most cases, modelling was carried out with a focus on the economic perspective [65] or the network operating perspective [27].

However, when assessing the environmental aspects of synergies, researchers point out that the use of a similar business model in different geographical regions can lead to significantly different results; for example, in European countries, the impact of such synergies may be greater than in many other regions [66], [68]. Therefore, in order to obtain the best results, it is necessary to make a comparison of different EV promotion tools for a specific country or region using specific parameters that characterize differences in transport use in a particular country, differences in the efficiency of PV equipment and peculiarities of development, etc. This study uses economic parameters and technical assumptions that characterize Latvia and similar countries or regions as Latvia. However, it should be noted that the developed model of system dynamics, by changing the corresponding technical assumptions and parameters, can be used for the analysis of other countries or regions.

An analysis of the actual load and structure of electricity network investments shows that the impact of electromobility on grid operating costs, contrary to concerns, can, in many cases, be positive [27], [110]. EVs can contribute to grid efficiency in cases where the actual network load is low, so the point of this research study is to determine the impact of possible dynamics of EVs on the required investments in electricity networks. The technical impact of EV charging infrastructure on the electricity distribution network has been extensively studied by many researchers [110], [140], [36], [37]; however, extensive studies on how the increase in the number of EVs will affect the operation of the electricity network from the point of view of the economy of their operation have been carried out on a relatively small scale, and in many cases are applicable only to the assessment of the economic performance of an individual network. Meanwhile, existing research focusing on the technical effects of electromobility provides several important facts for the related economic analysis. For example, modelling results show that a coordinated charging capacity allocation strategy and a well-managed charging strategy can increase the allowable number of theoretical EVs in the system by up to six times [26]. A study in Germany confirms that the technical impact of EV charging is highly dependent on local topology and capacity utilisation in the electricity grid [27]. Thus, studies confirm that where the available network capacities have a low overall utilisation rate, e.g. up to 30 %, the additional EV charging load has the same effect on the performance of the grid as any other additional demand for electricity [28]. This means that in the case of under-utilised network charging, electric transport can be used as a strategy to improve the overall use of the network and to carry out the economic optimisation of the network [29], [30]. Several other studies also show a close link between an optimised and adaptive strategy for the development of charging infrastructure for electric vehicles and their potential environmental impacts in terms of energy losses and carbon emissions [31], [32].

Estimates of industry experts in Latvia show that the development of EVs from the point of view of the development of electricity network infrastructure is related to two simultaneous trends. The first significant trend, according to the assessment provided by electricity network operators, is the expected increase in demand for investments in electricity distribution systems to ensure the safe connection of EV charging points to the grid and the provision of the necessary capacity for its further operation. Another important trend is the change in the total occupancy of the power grids. Data provided by Latvian electricity transmission and distribution system operators show that the total system capacity is significantly higher than the actual load of electricity system users, and in many cases, it is possible to increase the load even several times [33], [121]. Therefore, the purpose of this study is to determine the impact of EVs on the economic and operational performance of the electricity grid, considering the actual installed capacity of the electricity grid and the potential demand for EVs. The analysis shall include an assessment of the costs and benefits for electricity grid users of changes in the use of network capacity. The benefits in monetary terms of carbon emissions for society from the carbon avoidance of replacing fossil fuels in the light-duty vehicle sector with EVs are also assessed. Looking at the studies carried out so far, it can be concluded that synergies, integration and potential problems of solar energy and electromobility have been the focus of attention of researchers from a technical point of view, and studies confirm that electromobility can have a significant positive impact on the successful increase in the share of electricity produced by PV in energy systems. It can also serve as a technology for balancing short-term consumption from the point of view of energy system management, as well as ensuring the accumulation of excess electricity from PV [34], [35].

At the same time, it can be concluded that the range of studies assessing the potential for economic synergies between electromobility and solar energy and comparing them with alternative scenarios is significantly smaller, and their results are applicable locally. Local parameters and conditions specific to Latvia are discussed in this work and applied to the Latvian case study [104], [106]. Previous studies have shown that a number of economic parameters characterising the synergies between PV and EV charging technologies are largely due to the success of their technical integration into the energy system and their impact on the operation of electricity grid systems, and, for example, from a technical point of view, the researchers believe that both PV and EV charging technologies are complementary, but also contradictory in some ways [36], [37]. On the other hand, the insufficiently planned entry of EV chargers into the system could have a significant impact on a further increase in system maintenance costs [34]. At the same time, charging electric cars has the potential to become a technology that can also have a positive impact on the successful integration of other PV technologies into the electricity market, as the production of electricity from PV correlates closely with overall economic activity and energy consumption [38], and by incentivising electric car owners to charge vehicles during periods when electricity generation from PV is highest, it is possible to reduce the gap between electricity consumption and production in the system [39] and the likelihood of electricity prices reaching negative values as a result of significant excess electricity is reduced [38].

1.4. Technical and economic prospects for the decarbonisation of heavy transport through synthetic fuels

Industry experts predict that long-distance and high-power mobility, including air and ship transport, will continue to have to rely at least in part on liquid fuels in the future [2]. Synthetic fuels produced from electricity – e-kerosene, methanol, dimethyl ether (DME) and ammonia can be used in a similar way to fossil fuels in both aircraft jet engines and internal combustion engines of motor vehicles and ships, replacing conventional jet fuels, gasoline and diesel fuels.

In accordance with the objectives set out in the Doctoral Thesis, within the framework of its study, it is necessary to evaluate the technical feasibility of decarbonisation of the Latvian heavy-duty and long-distance transport sector (lorries, ships and air transport) with synthetic fuels obtained from hydrogen obtained from renewable resources and CO_2, evaluating the scenario in which the sources of electricity production are WPP and PV technologies. It is necessary to determine how much green hydrogen and CO_2 are needed to replace fossil fuels in those transport sectors with synthetic fuels. It is also necessary to assess how much of the electricity demand for the production of synthetic fuels can be supplied from renewable energy sources, i.e. PV and WPP energy, taking into account the installed capacity of these technologies and the excess capacity that can be used in the hydrolysis process for the production of synthetic fuels. The results of the study can be used to assess the necessary political and technical measures and their potential costs associated with successful decarbonisation in the heavy-duty long-distance transport sector, including the transformation of the energy sector. The technology discussed in the Thesis and carbon capture and utilization (CCU) technologies are already being developed [41], and CCU technologies, in addition to energy efficiency improvements and the use of renewable energy sources, could help decarbonise our economy [3]. The captured CO_2 can then be coupled to hydrogen produced by electrolysis and powered by RES to produce synthetic fuels produced from electricity [4]. At the same time, the high energy intensity of CO_2 capture processes, as well as the need for further purification, are some of the technical challenges, and the high costs pose economic challenges [43]. Public acceptance is very important for the deployment of CCU technologies, as is the case with other technologies, and this is linked to the social benefits of the technology [43]. Reducing production costs, namely the cost of electrolysis and the price of electricity is a key factor in making this fuel a competitive [42] synthetic fuel. The price of CO_2 emissions is also very important, and a certain minimum price level must be achieved in order for CCU to be possible [44]. Recently, however, we have seen an increase in CO_2 emissions and the price of fossil energy sources and can expect CCU technologies to develop further in the future. The production of green hydrogen provides flexible consumption for renewable energy sources of volatile development [45] as well as storage options for high-energy-density fuels [46]. Therefore, it is important to understand what are the environmental and socio-economic benefits that a synthetic fuel solution made from electricity can bring. In addition, it is also necessary to assess what support policies could be effective in promoting the use of technology, given that there is still a lack of research modelling the impact of the use of certain institutional support mechanisms on the dynamics of the development of technologies for synthetic fuels produced by electricity. The essential task of this study is to find out how important, in comparison with other technical-economic factors, is the support for technologies to produce synthetic fuels using CO_2, research and development, and what is the potential for reducing CO_2 emissions in the transport sector depending on these technical-economic factors? What is the sensitivity of the modelled system to technical, economic and institutional factors that may be important for the development of the business model to produce synthetic fuels?

1.5. The impact of changing sources of electricity production on the development trends of the electricity market and interaction with the transport sector

Renewable energy, in particular electricity produced by wind and solar technologies, is becoming an increasingly important source of energy supply both in European countries and in other regions of the world, and in certain periods wind energy can become the largest source of electricity production in the Nordic and Baltic region for a long time. Overall, there is a consensus that wind and solar energy are likely to put downward pressure on electricity prices [57]. However, falling electricity prices during periods of strong winds may jeopardise incentives for additional investment in renewable energy sources [5], [6]. Thus, anticipating future electricity price developments in relation to the wider spread of wind and solar energy is becoming an increasingly important task, as the industry will strengthen the view of the wider use of wind and solar energy as an inevitable direction in which the energy sector should develop [7][8]. However, current studies and forecasts do not provide a clear answer on the economic impact of such developments and policies to support wind and solar energy [49][9][10], while several previous publications and analyses [11], [12] were mainly based on daily or monthly statistics, while actual data from the Nord Pool exchange clearly show that price and production fluctuations are much more significant on an hourly basis. Intensive research work on the impact of wind energy production on the behaviour of energy markets has been carried out by several researchers for more than a decade, and several publications have shown that the increase in wind energy production and the subsequent increase in the share of wind energy in the total energy balance should lead to a gradual fall in wholesale electricity prices [6], [11][13][58]. A Swedish study covering the period 2000–2016 confirmed that with the increase in wind energy production by 1 %, the wholesale price of electricity fell by around 0.08 %, and in the longer term, the value of this reduction could increase to around 0.1 % [14]. While there are a significant number of publications analysing the impact of wind power generation and the increase in installed capacity of wind power plants on the wholesale electricity market, in many cases, researchers have focused their analysis on issues that may limit their applicability to long-term energy system modelling. Studies on the impact of wind energy on market electricity prices in relation to the availability of cross-border capacity in Denmark and Ireland show that high wind power generation, combined with the availability of good cross-border capacities, contributes to lower electricity prices and price convergence between different regions [15] [16]. However, these results also show that, from the point of view of the wind energy sector, a decrease in electricity prices in the wholesale market cannot always be considered a desirable market development trend, as it reduces the economic incentive for investors to invest in new generation assets and, in some cases, causes losses to market participants. The study also does not provide sufficient data to assess the correlation between wind energy production and prices in markets with a very high degree of economic and technical integration with neighbouring territories, such as the Baltic States, Denmark, Norway, Sweden and Germany. At the same time, several authors acknowledge that if predictions about the impact of wind and solar energy on electricity prices come true, industry experts will have to consider introducing new market mechanisms to maintain the economic sustainability of electricity producers in the long term, for example through capacity payments [5], [17], [[18]. Therefore, one of the tasks of the Doctoral Thesis is to study and analyse the actual correlation between wind electricity production and its share in the actual electricity demand with wholesale electricity prices in the Baltic States and selected Nordic countries in 2019. The obtained correlation data can be used to prepare further methodological approaches to energy system modelling, especially long-term modelling over a period of 20 years or more, and electricity prices have a significant impact on the use of electric vehicles and on the production costs and cost predictability of synthetic fuels in the long term. An additional result of the study is the possibility of determining whether the existing operating principles of wholesale markets such as Nord Pool are flexible enough to be adapted to the production of electricity as well, without compromising incentives for additional investment in renewable energy sources.

2. RESEARCH METHODOLOGY

To achieve the tasks set within the framework of the Doctoral Thesis and to complete the tasks, four different methods are used, which are shown in Fig. 2. The application of several methods allows the application of an integrated methodology based on theory to assess the feasibility of introducing measures to promote the neutrality of the transport climate, as well as the economic and technical feasibility discussed in the Doctoral Thesis. The methods used, illustrating the research tasks to be achieved and the results to be achieved by each of them, are reflected in Fig. 2.

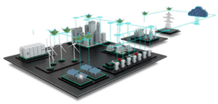
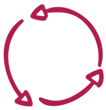
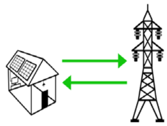
Transport and energy system modelling with the EnergyPLAN energy simulation modelling tool 	**Analysis of system dynamics with the Stella Architect modelling tool** 	**Statistical and economic cost-benefit analysis** 	**Technical-economic analysis** 
Analysis of the interaction between the RES electricity and transport sectors and the cost and emissions generated, taking into account seasonal fluctuations and infrastructure capacity.	Assessment of institutional aspects and analysis of the impact of business on the dynamics of the implementation of transport and RES policy measures, interrelationships and the importance of various factors.	Analysis of the correlation between the development of RES and wholesale electricity prices	Impact of electricity consumption and charging service development scenarios from the transport sector on the technical and economic operation of networks and end-user costs

Fig. 2. Methodological structure of the Doctoral Thesis.

2.1. Evolution of the increase in the number of EVs in the light road transport sector depending on technological developments and support instruments and changes in related CO_2 emissions

To study the development of light passenger electric transport, mathematical modelling using a system dynamics approach, i.e. system modelling, was used as a research method, creating it as a structure consisting of stocks and flows. The system dynamics model was created in the Stella Architect program [19]. The modelling time period is from 2021 to 2050 with a time step (dt) of 1/4 of the year, since the smallest time constant in the model is one year. Data from statistical databases, publications and reports were used. For individual data that could not be found in the sources of information, accepted values were used. The structure of the model is presented in the form of a causal loop diagram (CLD, Fig. 3), which reflects the main elements of the model and their interrelationships. CLD allows you to create a dynamic hypothesis about the possible behaviour of the system, but the hypothesis can only be tested in a quantitative model using stocks and flows.

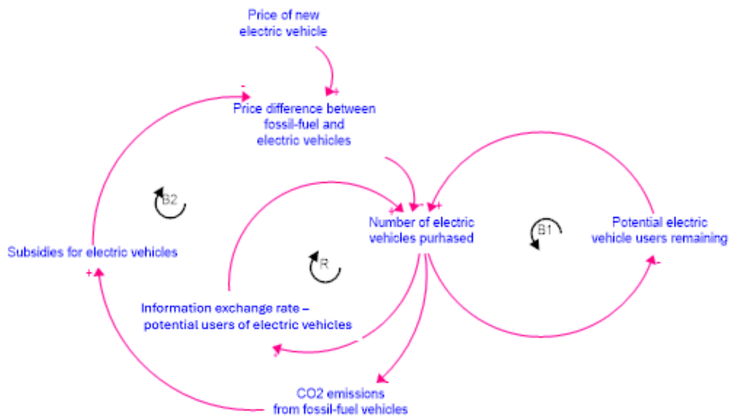


Fig. 3. Model's causal loop diagram (CLD).

Explanation: The "plus sign" in the diagram means that the increase/decrease in the cause causes the effect/decrease relative to the condition that would otherwise have existed if all other factors had remained unchanged. The "minus sign" means that an increase/decrease in the cause causes the effect to decrease/increase in relation to the condition that would otherwise have existed if all other factors had remained unchanged.

The set of EVs reflected in the stock “'Number of EVs purchased”' (Fig. 4) is the most important parameter in the model that influences the overall CO_2 emissions of light-duty vehicles. This inventory is controlled by the flow "Number of EVs purchased" (Fig. 4). As the number of "EVs purchased" increases, the frequency of contacts between EV users and potential users also increases, and because of information exchange, even more EVs are purchased in the future. This is the reinforcing (positive) feedback R (Fig. 4), which has the most significant impact in the early stages of EV stock growth. As the number of "EVs purchased" increases, the stock of "Remaining potential users of electric vehicles" is depleted, and the growth rate of the "Number of EVs purchased" indicator begins to decrease when balancing (negative) feedback B1 becomes stronger than the aggravating effect R. The "Number of EVs purchased" is strongly influenced by the "Price difference between fossil fuels and electric vehicles" (Fig. 4). The price difference, on the other hand, depends on "Subsidies for EVs" and "Price of new EVs". “Subsidies for EVs” is an endogenous parameter as it can be influenced by the parameter “CO_2 emissions from fossil fuel vehicles”. The difference between actual CO_2 emissions in the transport sector and the CO_2 emissions target may influence the policy decision. The larger the gap, the more politicians are willing to give subsidies for the purchase of EVs and vice versa. This is a balancing feedback, B2, as an increased number of "EVs purchased" reduces "CO_2 emissions from fossil fuel vehicles" and reduces the "Subsidies for electric vehicles" (due to reduced political will), resulting in a greater price . A larger price difference means a reduction in the number of EVs purchased. Only purchases of new EVs are considered in the model. The "Price difference between fossil-fuel vehicles and electric vehicles" is also influenced by the "Price of a new electric vehicle", which is an exogenous parameter in the model.

The model contains sub-models of stocks and flows (Fig. 5) for the calculation of the number of EVs, the dynamics of the installation of charging equipment and PV at service stations, the share of energy produced by PV and the resulting reduction in CO_2 emissions. The model also takes into account economic factors such as subsidies for the purchase of EVs, investments in EV charging infrastructure and PV, as well as charging costs.

The dynamics of the increase in the number of EVs purchased depends on the total amount of subsidies, reflected as a stock, and on the subsidies per new EV, which is displayed as a parameter. EV acquisitions reduce the subsidy fund, and when it is exhausted, a new amount is injected into the stock with an interval of five years.

The cash inflow into the subsidy fund depends on the difference between actual and target CO_2 emissions, the price difference between EV and FV price is a decisive factor in the decision to purchase EVs. As the price of a new EV decreases, the share of subsidies for a new EV will increase, and without changing other conditions, this will increase the incentive to buy a new EV. The number of EVs in the country determines the amount of electricity consumed for charging EVs, the construction of charging infrastructure at gas stations, as well as the development of solar PV.

A separate module (Fig. 5) is used to determine the speed at which EV charging units should be installed at gas stations. The number of already existing gas stations and charging infrastructure are considered. Since the maximum number of EV charging units at gas stations is assumed to be six, the installation of charging units outside gas stations was also considered. The decision to invest in the installation of a PV system is made only if the current net value for this investment is equal to or greater than zero. This means that the price of grid electricity must be high enough to generate the necessary cash flow of energy cost savings.

The main result of the model is the reduction of CO_2 emissions, which is achieved by replacing fossil fuel vehicles with EV vehicles. It is assumed that the overall size of the vehicle fleet will remain unchanged, and the study did not take into account the dynamics of the FV fleet in relation to the fuel combination used, age and the resulting CO_2 emissions per km. Changes in the structure of electricity generation with regard to grid electricity were also not taken into account. Therefore, it was assumed that the CO_2 emission factors for FV and electricity are constant.

2.2. Assessment of the potential impact of light EVs and different charging infrastructure development scenarios on electricity grid operations.

To assess the possible impact of light EVs and various charging infrastructure development scenarios on the electrical load profile in the electricity grids and the technical and economic efficiency of the networks, the study used hour-by-hour modelling of the

Latvian energy system for the whole of 2050. As a tool, the advanced energy system analysis modelling software EnergyPLAN was used. The focus is on the use of RES sources, looking at a scenario in which the amount of electricity produced by RES could fully cover all the electricity needed by EVs. The functionality of the model assumes the possibility of including electricity produced using wind, solar and hydropower. In the transport sector section, it is possible to model the impact of the transport sector on the overall national electricity grid. For 2050, the study looks at a scenario of completely phased-out fossil fuels and a fleet consisting solely of EVs. This assumption is essential to be able to determine the expected maximum electrical load with the help of a tool.

According to the forecast, in 2050, the number of passenger vehicles in Latvia could already exceed 1.1 million light vehicles. To obtain the total electricity consumption of EVs in 2050, it is important to determine the total number of EV users (total number of vehicles in 2050), average mileage of a car (13 000 km [20]), and the average electricity consumption measured as 199 Wh/km (aw) [21]. The calculation is carried out by multiplying the three above parameters and using Equation (Eq. 1.).

$$tec = evn \cdot am \cdot aw, \tag{1.}$$

where

am - average mileage per car, km /(number of vehicles x year);

aw - average EV power consumption of ETL, Wh/km;

tec - total power consumption in relation of EV usage, Wh/year.

During the study, coefficients were also developed that allow to reflect the impact of various habits of using the EV charging service on the operation of the electricity system, predicting the consumption load depending on what type of charging (by its speed) is used to ensure the consumption of EVs. The coefficient values are based on realistically collected data describing the habits of EV users to charge their vehicles over a certain period of time, thus obtaining the values of the coefficients every hour, year [22], where specific coefficient values were created by obtaining electricity meter data from several charging points (including households), as well as describing the usage habits of charging stations for EV users.

For this study, the input data coefficients will be summed up from the acquisition coefficients that were divided into home, public and fast-charging types in the above work.

In order to be able to determine the maximum possible overall coefficient between these three types of coefficients, it is necessary to provide a percentage of aid by which the proportion of each type of EV charging station can be determined. However, the percentages are indicated as a fixed value throughout the year, and unlike hourly coefficients, they will not change. The obtained results also demonstrate the overall impact of EV charging on the operation of the energy system in Latvia. They consider the available data on the electricity consumption for home EV charging, public slow EV charging and fast charging.

When assessing the possibility of meeting the energy demand generated by the transport sector, modelling forecasts for the expected development of renewable energy production capacities (mainly VES and PV) in the electricity sector were also considered. In order to develop forecasts, the total potential for the development of renewable energy capacities was taken into account, which is justified by the assessment of the system operator regarding the actual potential of the PV and VES in the territory of Latvia and the possibilities of electricity transmission infrastructure. The forecasts also consider the deadlines necessary for the development of production projects and infrastructure, as well as the expected time needed for the development of cross-border infrastructure.

The simulation of the energy system also examined a scenario in which, in 2050, the Latvian electricity demand is covered only by renewable energy, using electricity produced by VES, PV and hydroelectric power plants as primary sources.

The study examines several possible scenarios for the development of charging infrastructure and their interaction with the energy supply balance.

Scenario with priority home charging profile "70-5-25": The overall odds have been calculated and related to the first modelled scenario for 2050, in which the charge of the dwelling is prioritized, and the scales correspond to the 2021. This means 70 % weight for home charging, 5 % weight for public and 25 % weight for fast charging option.

Scenario with priority fast charging profile "35-10-55": The second scenario for 2050 examines the priority of fast charging stations and their impact on the overall power grid. In this scenario, the choice of scales assumes that in the future, as the number of EV users increases, there will be a shortage of charging stations near apartment buildings. This would mean that more users would look for opportunities to use fast charging stations.

Weight is given accordingly: 35 % for home charging, 10 % for public, and 55 % for fast charging stations.

Looking at the impact of EV charging on main peak loads in a scenario with a higher priority for fast charging, it can be concluded that changes in the charging scenario have identifiable effects on consumption loads on hour-by-hour basis; however, there are no significant differences between peak load hours. On the other hand, looking at the impact of the scenario on the performance of the energy system on a weekly basis, it can be concluded that changes compared to the previous scenario are observed during peak hours. If, for home charging, these hours of maximum consumption load were much more pronounced, then for fast charging, they are smoother. In the middle of the analysed week, the picture did not show any pronounced peaks, and the entire period of the day continued with equal demand.

To compare the charging load variations of the two scenarios and their impact on the power grid, load schedules for each season of the year were modelled, and it can be concluded that the type of curves of the two scenarios are relatively similar during the winter months. The home charging scenario "70-5-25" has bigger peaks in the evening hours, but the overall peaks for both graphs are similar. The fast-charging scenario "35-10-55" has a greater impact on the hours of the day. Although all values are similar, in a scenario that assumes a higher proportion of home charging, higher power peaks are observed. This can also be seen by the annual maximum capacity demand value. This value is almost 200 MW higher in the scenario, which assumes a higher share of home charging, which means that power generation technologies capable of providing such capacity will be required at a certain hour.

Modelling of the impact of EVs on the network load was performed using Latvian data on the total electricity demand for needs not related to electromobility, as well as the total installed capacity of the network. For parts of this study, a few assumptions were made about the characteristics of EVs and fossil fuel-derived passenger vehicles, as well as specific CO_2 emissions and costs. The calculations are made on the assumption that the annual number of investments in the electricity distribution system is maintained at the existing level. This assumes that the increase in the number of EVs in all cases is not due to the need to invest in the power grid. The results of some studies show that by integrating

EV charging infrastructure into the network, network operators have a wide range of options for optimizing the network load. Thus, the volume of planned investment in networks should be considered as a decision that is mainly related to the overall investment and regulatory policy of the network or even policy decisions and not as a parameter directly related to consumer demand. However, the model also includes the possibility of comparing scenarios with additional investments in the network. The analysis carried out helps to assess how the development of EVs can improve the economic performance of the existing electricity grid infrastructure. It can also be used to simulate the results of alternative scenarios with variable parameters such as additional investments in the grid, changes in the structure of electricity tariffs or tariff changes.

Studies on the development of EV charging infrastructure so far have shown that a significant impact on the demand for different types of EV charging devices can develop in several possible scenarios, each of which is characterized by a different potential impact on network load as well as user behaviour. It has been found that EV users generally prefer to charge in the household (about 50–80 % of cases) as well as in workplaces (from 15 % to 25 % of cases), with only about 10 % of charging taking place in public, publicly accessible charging points [23]. It should be noted that, unlike many other energy consumption habits of society, electromobility does not have a single common and pronounced consumption trend, which would accurately reflect its impact on network performance.

From the electromobility study, it can be concluded that the overall planning of electric charging stations is usually optimised, which ensures the availability of charging service depending on the mobility habits of the region (e.g. average travel distance, urban or extra-urban mobility). Optimized planning significantly reduces the overall charging density of EVs in each area, as well as the required electrical power of these charging stations [24]. The results of the studies show that both the need for a specific density of charging stations in a particular area and the resulting impact on the network largely depend on the population density, as well as on the technical characteristics and condition of the existing network. The assessment of the network capacity shows that the Latvian power grid is potentially able to provide a theoretical demand load that exceeds the existing load by up to 4 times. Studies also show that the total EV charging simultaneity rate is not significantly different from the total factor for other types of consumption, as approximately only 78 % of transport is used daily, and the simultaneity factor for EV charging reaches only about 50 % in the most extreme scenarios [25]. The assessment confirmed that the total capacity of the network is still sufficient to ensure the complete replacement of all registered and actively used vehicles (including lorries and passenger buses) in Latvia, corresponding to approximately 1 million vehicles.

In a study assessing the impact of the use of electric transport on the cost of network services and the total cost of mobility at the level of an individual user, modelling was carried out using existing public distribution tariffs, publicly available electricity and fuel prices, as well as publicly available information on the prices of specific car models. The modelling was carried out using a model created in Microsoft Excel and based on formulas that considered the following values: variable and fixed costs related to network services, their fluctuations according to different scenarios; costs associated with the supply of energy (in the form of diesel fuel or electricity); and the costs of using electricity for non-mobility purposes. The analysis is performed for each of the scenarios described in the study below.

Several assumptions about economic factor parameters and related impacts were made or derived from industry statistics and are based on a scenario where EV charging for the accepted mobility needs is provided by household electricity connection. There is reason to believe that the effect of economic synergy between solar energy production equipment and EV charging technologies in Latvian conditions is primarily important for a scenario in which both solar energy production equipment and EV charging equipment belong to the user and are connected to the public network with one connection. To assess the economic impact of the synergies, it is useful to compare the economic benefits and costs to the user with a few alternative scenarios (Table 1).

To ensure the fullest possible comparison of the synergy scenario of solar and EV charging with different alternative economic scenarios, a comparison was made between the final cost per unit of energy (kWh) for total energy consumption and the final cost of energy consumption, considering both energy consumption for transport purposes and other needs. Such a comparison would be justified by the fact that, according to the structure of the Latvian electricity distribution tariffs, the costs of electricity consumption for the final customer, in addition to different energy use scenarios, are influenced not only by the electricity consumed but also by a number of other factors – for example, efficiency and intensity of the connection load, the applicable tax rates, as well as the user's habits [26], [27].

Table 1

User Mobility and Power Supply Scenarios Used for Modelling

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Power supply from the network	Used	Used	Used	Used
Power supply from PV	Not used	Not used	Used	Used
EV	Not used	Used	Not used	Used
FV	Used	Not used	Used	Not used

2.3. Modelling the electrification of heavy transport with the help of synthetic fuels, considering the development of RES capacities and the impact on the network

The previous study has concluded that the decarbonisation of light passenger transport through the switch to EVs is economically justified and technically feasible; however, the electrification of freight transport is significantly limited by the fact that the intensity of use of lorries in general is significantly higher than that of light transport. This study assessed the most plausible scenario, the decarbonisation of heavy transport through synthetic fuels produced from electricity sources. In this study, which aims to determine the technical prospects for the decarbonisation of heavy transport with synthetic fuels, modelling of the Latvian energy system was carried out using the EnergyPLAN tool [28], also considering the expected development of renewable electricity generation capacities. The application of the model to Latvia was based on the development forecasts provided by the transmission system operator and other institutions responsible for the energy sector. To justify the use of the model, its validation was carried out, which included modelling the economic and energy balance of the Latvian energy system for 2017 and a comparison of the obtained results with the actual indicators of this year. The input of the model was such system parameters as power, production and investment of various energy sources. These parameters are be applied separately to specific, predefined scenarios reflecting the impact of specific investment decisions and policy measures. To assess the development prospects of the Latvian energy system, and to determine the expected development of renewable electricity production capacities, as well as their impact on the reduction of carbon emissions, five different scenarios were used. A detailed description of the parameters for each scenario is provided in Table 2, providing that the wind power capacity limit of approximately 1200 MW is set according to the existing capacity of the high-voltage grid and the availability of energy resources for balancing wind energy.

Table 2

Key Input Parameters and Assumptions for Modelled Scenarios

Input parameters for scenarios and accepted values	**Business as usual scenario**	**RES scenario**	**Energy efficiency scenario**	**Combined scenario**	**Flexibility scenario**
1. Power consumption yearly (TWh)	13.85	13.85	9.87	9.87	16.46
2. Installed PV (MW)	41	300	41	300	129
3. Installed WPP (MW)	678	1200	678	1200	978
4. Average yearly heat consumption (KWh/m^2)	95	95	43	43	95
5. Number of EVs (thous.)	300	350	350	350	550
6. Average investment for renovation of buildings (EUR/m^2)	70	100	200	200	100

The analysis of the results of the scenario modelling confirmed that, in general, both from the point of view of technical and economic considerations, the electricity supply of

Latvia with renewable energy sources is technologically and economically feasible, and their volume is sufficient to ensure also the possible demand of the transport sector. Against this background, additional scenario modelling and analysis were further developed to consider the potential impact of the transport sector on the functioning of the energy supply system, complemented by updated data and modelling on the basis of the latest available data. Modelling future scenarios for 2050 identified the necessary wind turbine capacities to meet the energy demand to produce hydrogen and further synthetic fuels that meet the demand for trucks, ships and aircraft. A model of the existing system based on the Latvian energy balance for 2021 was created and validated. This model was then used to create three future scenarios.

When assessing **the demand for synthetic fuel**, the study considers that in 2019 almost 830 thousand land vehicles were registered in Latvia, of which about 12 % were heavy-duty trucks [29]. Although the number of vehicles is increasing every year, the total share of heavy-duty trucks is still about 12 %. To predict the number of heavy-duty trucks in the future, statistics from 2010 to 2019 were used [29] And future forecasts were made with a linear trend. Data on the fuel consumption of sea and air vehicles were obtained from the energy balance [30]. However, it was considered that the fuel consumption of heavy-duty trucks in the energy balance is not separated from land passenger vehicles, so additional calculations were made to obtain the data. Sources [31], [32] were used to find out the number of light vehicles, the average annual mileage in kilometres per vehicle, and the average fuel consumption per 100 km for passenger and heavy vehicles separately. Using the forecasts of the Latvian electricity transmission network operator [33], a forecast was also made on electricity consumption, power plant capacities and cross-border transmission network capacities for 2050. To fully decarbonise the heavy-duty and long-distance vehicle sectors, 8.2 TWh of fossil fuels need to be replaced by synthetic fuels. But to be able to produce this volume of synthetic fuels at a time when there is a surplus of renewable electricity, and not at a time when the transport industry is demanding it, it is necessary to create fuel storage tanks. It is estimated that a total of 10.64 TWh of hydrogen – 6.02 TWh of DME, 4.59 TWh of e-kerosene and 0.03 TWh of ammonia – are needed to produce 8.2 TWh of synthetic fuel.

To evaluate the business and institutional aspects of the dynamics of the

implementation of synthetic fuel technologies, system dynamics modelling was used to approbate the model using ethanol. The model was designed and approved to produce synthetic fuel ethanol; however, it is also applicable to other synthetic fuel production technologies. An important feedback loop is the link between CO_2 emissions avoided and the share of synthetic fuels in the transport sector to investments in ethanol production capacity.

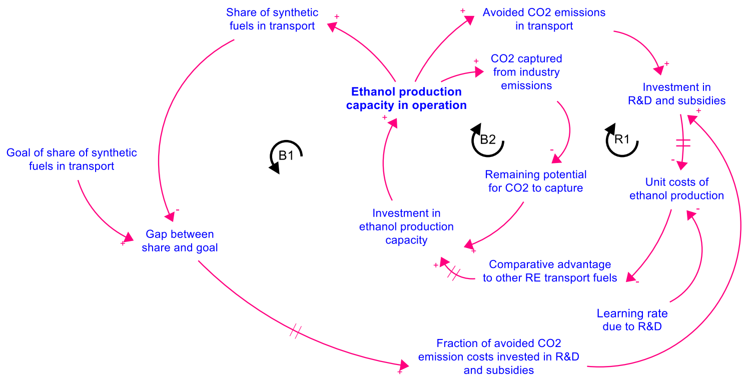


Fig. 4. Model's causal loop diagram (CLD).

(R&D – research and development; RE – renewable energy; R1 – reinforcing or positive loop No. 1; B1 – balancing or negative loop No. 1; B2 – balancing or negative loop No. 2). The "plus sign" means that because of the increase/decrease of the cause, the effect increases/decreases relative to what would otherwise have been the case if everything else remained the same. A "minus sign" means that an increase/decrease in the cause causes the effect to decrease/increase relative to what would otherwise have been the case if everything else had remained the same. Two vertical lines on the arrows indicate that the time gap between cause and effect can be relatively long.

Feedback is influenced by the difference between the actual share of synthetic fuels in transport and the target value to be achieved. The main goal of modelling is to develop a model that can be applied to further research using various possible development scenarios [34], which allows for a comparison of the expected estimated impact of different policy measures rather than providing accurate forecasts. The model aims to support the cognitive process, scenario analysis, interaction of expert groups, policy development, and systems aimed at providing data to solve problems. The model was created using expert team workshops and is integrated into an interactive simulator that can be used to test policy scenarios. Ethanol was chosen as the final product of CO_2 hydrogenation because it is widely used in transport [35]. The thermochemical synthesis of ethanol from CO_2 considered in the study using dimethyl ether (DME) synthesis was chosen due to the relatively high overall energy efficiency and degree of CO_2 conversion [4]. The CO_2 capture technology chosen in the study was chemical absorption by amine purification in the scrubber. This technology was selected in the study due to its high level of technological readiness [4]. Alkaline electrolysis was chosen as the H_2 production technology due to the maturity of the technology to produce large-scale hydrogen [4] and good energy efficiency [36]. Capital investment in ethanol production capacity may be significantly overestimated compared to the data used in [37]; however, investments depend on the size of the plant, geographical location, available infrastructure, year of construction, etc. The structure of the model is presented in the form of a causal loop diagram (CLD). which reflects the main elements of the model and their interrelationships. CLD allows you to create a dynamic hypothesis about the behaviour of the system, but the hypothesis can only be tested in a quantitative model using stocks and flows.

Ethanol production capacity is a key stock in the model, as only real investments in physical production assets can result in the use of renewable energy sources. Investments in ethanol production capacity are made when the cost of production of the ethanol unit is competitive with the unit cost of producing alternative biofuels. The share of capital investment in ethanol production capacity is determined by comparing the cost of production of an ethanol unit with the cost of production of an alternative biofuel unit in the LOGIT function.

The public may decide to support the development of synthetic fuel technologies by funding research and development and subsidising ethanol production. The source of funding for research and development and subsidies could be the income that can be generated by reducing CO_2 emissions in the transport sector if fossil fuels are replaced by ethanol. The source of funding could be CO_2 emission allowances, which could be sold, or funding that has not been spent on the purchase of emission allowances. R&D funding and subsidies make ethanol even more competitive, which makes it possible to increase ethanol production capacities even further. As a result, even more CO_2 emissions are avoided, which in turn makes it possible to allocate even more funding for research and development, as well as subsidies. Thus, the reinforcing loop R1 is created. This is the main institutional aspect of the model. It could be argued that this mechanism would be difficult or impossible to implement, especially if the transport sector is not part of the emissions trading scheme. However, we can monetise the CO_2 emissions avoided in one way or another (e.g. through an external cost approach) and decide that part of the avoided cost of CO_2 emissions is invested in research and development or subsidies, which would further increase the benefits in the future. It is a political decision that should be made, and the model illustrates the consequences of such a political decision. The model assumes that the share of CO_2 emissions avoided is used to finance R&D and subsidies based on the difference between the actual state of the system and the climate target in a given transport sector. If the gap between the target and the actual share of synthetic fuels in the transport sector narrows, the incentive to finance R&D or to subsidise ethanol production may also be reduced, and funding is reduced with a certain time lag. Thus, a balancing loop B1 is formed (Fig. 19). This balancing effect produced by the reduction of stimuli when approaching the goal is characteristic of the behaviour of the "pursuit of the goal" systems, including systems describing the implementation of climate and energy policies. The difference between the share of synthetic fuels in transport and the share target is measured as the ratio between the actual share and the target, which varies from 0 to 1. When the target is fully achieved, the ratio becomes 1, and funding for research and development and subsidies for ethanol production is not allocated. If the ratio is less than 1, the funding is increased non-linearly until it reaches 1, i.e. all funding available from the avoided cost of CO_2 emissions goes to research and development and subsidies for ethanol production.

As ethanol production capacity increases, so does the share-to-target ratio of synthetic fuels in transport (if total fuel consumption in transport does not increase), and funding invested in R&D and subsidies decreases. The synthetic fuels target for transport is assumed to be 2.6 %, which is in line with the 2030 value discussed in Latvia in relation to transport targets, in line with the EU Fit for 55 climate initiative. The target may be increased beyond 2030, but there is currently no information on the potential value. In addition, synthetic fuels will cover only part of the transport sector's needs, as some will be electrified, and other fuels, such as biofuels, biomethane, etc. are likely to be used. Given these considerations, the target for the share of synthetic fuels in transport is considered an external (independent of model calculations) parameter in the model.

However, the ability to adjust the target when it is achieved is important evidence of the institutional capacity to set climate targets, and therefore this target could be included as an internal (dependent on model calculations) parameter in future studies. The evolution of the funding allocated to research and development and subsidies is shown as the ratio between the actual funding allocated (in each period) and the maximum value of the funding allocated . Initially, the funding is low due to the small ethanol production capacity and the accumulation of funding from the avoided CO_2 emissions. Gradually, as ethanol production capacity increases, the allocated funding also increases, reaching a peak precisely when the actual ratio of the share of synthetic fuels in transport and the target reaches 1. After that, the allocated funding begins to decrease. However, by this time, R&D has already made the cost of ethanol production competitive with alternative fuels and, therefore, ethanol production capacity continues to increase, reaching the threshold when the amount of CO_2 captured by industrial processes reaches the maximum limit. From this result, it can be concluded that the balancing effect B1 is not the main limit of growth, and the main balancing loop could be B2, i.e. the raw material to produce ethanol. It should be noted that the model assumes that 50 % of the total funding is allocated to research and development and the same share of subsidies for ethanol production to reduce unit production costs.

The concept of using the speed of learning is borrowed from the field of energy, where it is used to characterize the specific decrease in capital investment in various energy production capacities, doubling the global installed capacity [38]. The speed of learning is considered an external parameter in the model. In the analysed system, another balancing effect can be identified. As ethanol production capacity increases (Fig. 19), the amount of CO_2 emissions captured from industry also increases. As captured CO_2 emissions increase, the potential for capturing CO_2 emissions in the future decreases, as the amount of CO_2 emissions that are practically captured from industrial processes is limited. As we approach this limit, fewer and fewer of these processes can be perceived as capturing the remaining emissions becomes too expensive or technically difficult. As the CO_2 capture potential decreases, so does investment in new ethanol production capacity.

2.4. Modelling of the impact of RES on the electricity market and interaction with the transport sector

The analysis of the impact of variable sources of electricity production on the development trends of the electricity market is based on a statistical analysis of actual prices and electricity development data for 2019, including hourly prices of the Nord Pool energy exchange for specific countries, physical production of wind energy in each specific hour and share of wind electricity in the total electricity consumption in each hour. The data was collected and processed with Microsoft Excel to find out whether there is a significant correlation between wind production and electricity prices, i.e. whether higher wholesale electricity prices result from a lower share of wind generation and vice versa, whether an increase in the development of wind power plants contributes to a fall in prices. To more accurately characterize the data obtained, the calculation of the correlation coefficient was additionally carried out. Considering the availability of hourly data of the Nord Pool stock exchange and national network operators for specific countries, the analysis was carried out for two regions – Denmark, which consists of two trading zones, and the Baltic region, which consists of the trading zones of Latvia, Lithuania and Estonia. The hourly price for each region was calculated as the average price for the county, while the production of wind energy for each region was calculated as the sum of wind energy production in the respective areas. The share of wind energy in the electricity balance was calculated as a percentage of the share of wind energy production in the respective territories in the total electricity demand in these territories. In addition, to compare possible correlation differences between hourly and daily market prices and the corresponding production, an analysis was carried out for the wider region, including Denmark, Finland and the Baltic States. In this case, the volume of wind energy production was accounted for by the sum of wind energy production in all countries, while the daily price was the average daily price of the system on the Nord Pool exchange, which also includes the trading zones of Norway and Sweden. Swedish and Norwegian wind energy production statistics were not included in the analysis because daily or hourly data from these countries were not available. However, data from both Nord Pool and Norwegian network operator Statnett show that the Nordic and Baltic regions are relatively homogeneous from the point of view of wind energy production. Daily, high wind energy production in one of the countries indicates high or medium-high wind energy production in all Nord Pool areas.

In addition, an analysis of two shorter time periods was carried out in the territories of the Baltic States, Denmark and Finland in order to compare wholesale prices in a situation where the only significant variable parameter was the production of wind energy, but other important factors, such as electricity demand, the availability of hydropower resources, which are characterized by storage facilities in Finland, Norway and Sweden, and ambient air temperature were similar.

To ensure sufficient reliability of the accepted research method when making forecasts of renewable energy development trends and related economic impacts, including the impact on market performance and total user costs, a model was developed in the EnergyPLAN modelling tool and validated the developed model**.** To determine the accuracy of the modelling, the actual statistical data for 2017 were compared with the outcome data of the EnergyPLAN modelling tool. The model provided a sufficiently accurate seasonal distribution of electricity and heat supply according to hydrological conditions and typical heat demand, as well as provided accurate estimates of the average demand for electrical load and heat load for each month of the year. In addition, the validation also provides very realistic estimates of the availability of wind and hydropower in the different months of the year. In the subsequent phases of the study, a comparison of the results of each scenario was carried out according to several parameters: carbon dioxide emissions, annual costs of energy supply (consisting of both variable costs and fixed costs such as capital costs in the energy sector), total demand for primary energy resources, and the volume of electricity imports or exports. However, to pay more attention to the results of the economic and environmental sustainability of the energy system, the subsequent analysis focuses on two most important parameters: carbon dioxide emissions and the total annual cost of energy supply.

When comparing the results of the modelling from the point of view of carbon dioxide emissions, all the development scenarios described above, including the Business-as-you-go (BAU) scenario, foresee a significant reduction in carbon emissions over the analysis period. On the other hand, the Flexibility Scenario (FLEX), even though it predicts the highest total energy consumption, shows the lowest amount of carbon dioxide emissions. The results confirm that transport remains one of the most significant sources of carbon emissions in Latvia, and replacing fossil fuels with energy sources such as electricity can lead to very significant results in reducing carbon emissions [116].

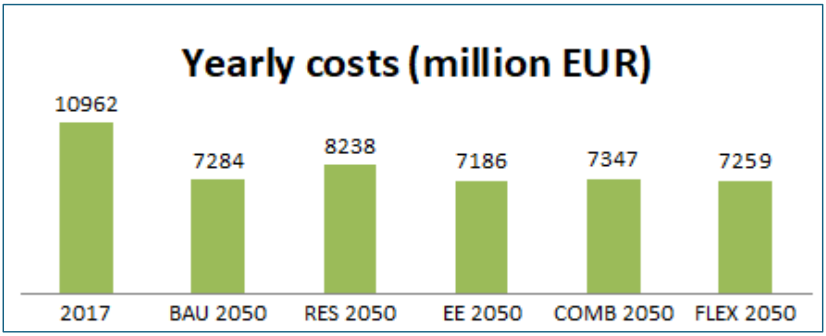


Fig. 5. Comparison of the modelled scenarios from an annual carbon dioxide emissions perspective.

Meanwhile, an annual cost comparison shows that the Energy Efficiency Scenario (EE), the Flexibility Scenario (FLEX) and the Combined Scenario (COMB) offer the most significant financial savings for the overall economy.

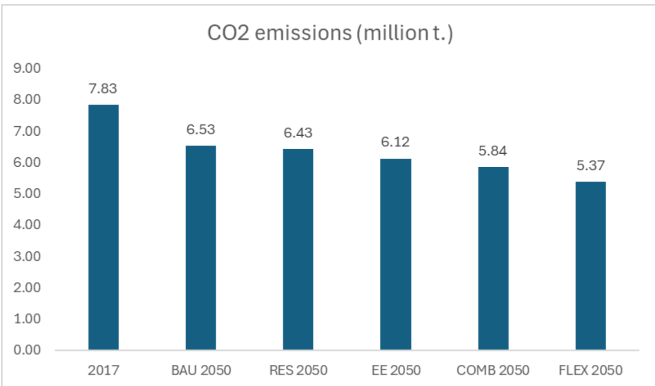


Fig. 6. Comparison of the modelled scenarios in terms of the total annual cost of energy supply.

A comparison of the analysis scenarios also indicates that the future use of parameters such as primary energy consumption as an essential indicator for assessing the sustainability of the energy system and policies may not be justified, as primary energy consumption does not correlate with a relevant indicator such as carbon **emissions**.

3. RESULTS

3.1. Evolution of the increase in the number of EVs and CO2 emissions depending on technological developments and support instruments

The most important objective for the deployment of EVs and the development of PV-based charging infrastructure at gas stations is the reduction of greenhouse gas (GHG) emissions. In line with the research assumptions set out in the Thesis, the gradual replacement of fossil fuel-based vehicles (FVs) with EVs and the installation of PV should reduce CO_2 emissions. The results show that FV emissions are being reduced, and only CO_2 emissions associated with grid electricity remain at the end of the modelling period. However, the reduction in CO_2 emissions is small until 2040, when change begins to occur very rapidly. This is due to the large price difference between EVs and FVs, even with subsidies starting in 2022. The model's assumption is that if the difference between subsidised EVs and FVs exceeds EUR 5000, EVs are purchased only by those citizens who do not need subsidies, and the share of this population is assumed to be around 20 %. When the price difference reaches EUR 5000 and is smaller, citizens who need subsidies for the purchase of EVs also get involved. The S-type schedule of the purchase decision shows the share of the population that needs subsidies when deciding to purchase EVs if the price difference decreases. However, even if a large part of this population is willing to buy EVs, a relatively small amount of EVs can be subsidised due to the limited overall budget allocated to EV subsidies. A significant increase in the number of EVs begins only at the moment (around 2040) when the price difference reaches 4500 EUR/vehicle, and from now on, no subsidies are required (Fig. 21). As the number of EVs increases, the electricity consumption of the electricity grid and CO_2 emissions associated with electricity generation are also starting to increase. However, this amount of emissions is significantly lower than the amount produced by FVs.

The price difference between an EV and a fossil fuel vehicle is narrowing due to the development of EV production technologies, i.e. as a result of the "learning effect". The effect is modelled as part of the assumed price reduction on a yearly basis.

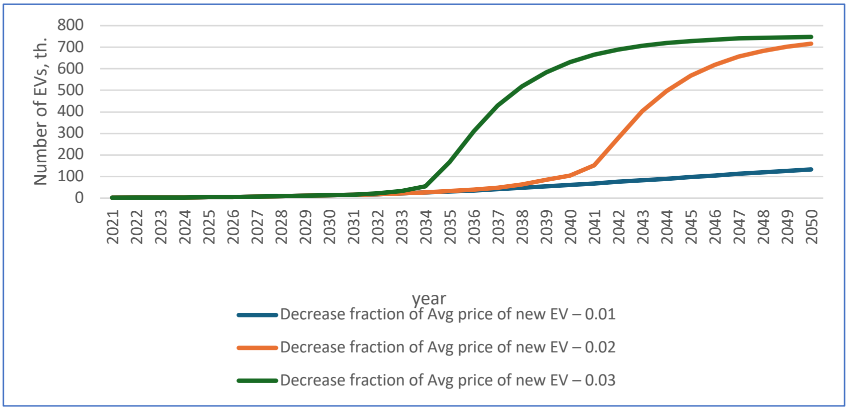


Fig. 7. The growth dynamics of electric vehicles depending on the rate of reduction in the average prices of new EVs. The average price undercutting in the baseline scenario is 0.02 per year, and in the other two scenarios, 0.01 and 0.03, respectively.

PV panels at gas stations where EV charging electrical equipment is built are installed relatively quickly and reach their maximum capacity in the fifth year (Fig. 7) since the cost of generating electricity is competitive with grid electricity from the very beginning of the calculation period. The amount of electricity produced at gas stations using PV placed on the roofs of gas station buildings is about 2 % of the total electricity required to charge EVs. Due to the relatively small amount of electricity generated from PV panels installed at gas stations, the possibility of installing PV at other charging points located outside gas stations is being considered in order to obtain a higher share of renewable energy. The results show that PV panels located outside gas stations can provide about 14 % of the total amount of electricity needed to charge EVs.

This low charge of solar energy use on electric vehicles is due to the fact that the main driver of the purchase decision is the price difference between EVs and FVs, and most EV purchases occur after the difference between the price of subsidised EVs and the price of FVs disappears due to the development of EVs. Therefore, subsidies per EV play an important role in the purchase decision, and if these subsidies per EV are doubled, then a significant increase in the number of EVs begins much earlier, and by 2050 the entire stock of FVs is replaced by EVs. A faster rate of replacing FVs with EVs also results in lower cumulative CO_2 emissions during the calculation period, although total annual CO_2 emissions will remain equivalent at the end of the calculation period. Sensitivity analysis of cumulative total CO_2 emissions (Fig. 8) shows that increasing subsidies from EUR 1000 to EUR 10 000 per vehicle reduces total cumulative CO_2 emissions by more than 50 %, provided that other parameters are not changed.

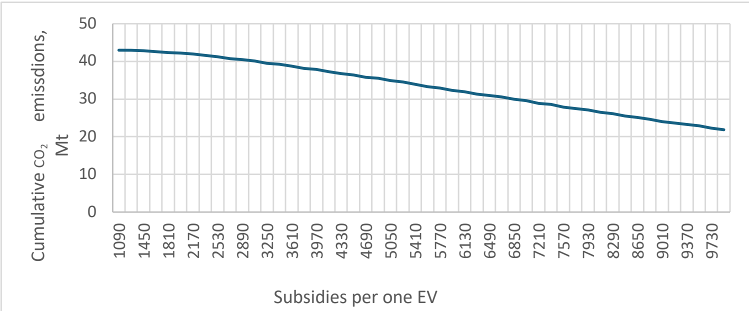


Fig. 8. Cumulative total CO_2 emissions depending on subsidies for new EVs.

3.2. The impact of the development of EVs on electrical load profiles and technical and economic indicators of electricity infrastructure

The electricity system operation simulation model used in the study also makes it possible to assess the impact on the electricity balance of different types of renewable energy scenarios and scenarios of electricity consumption of vehicles, including the ratio of production and consumption. The study assessed as the most optimal scenario the one where electricity consumption and production volumes within the national energy system are as balanced as possible, reducing the need to use cross-border infrastructure for energy supply, as well as contributing to a reduction in the impact of a significant surplus or shortage of electricity on prices.

In the modelling scenario, which assumes that EVs are primarily charged at homes, peak loads are observed in the evening hours, so imports are required during these evening hours, while in the fast-charging scenario, charging loads are observed in the middle of the day, also correlated significantly more with the development of electricity. As the graph shows, the production of other renewables also covers a significant part of demand.

In winter and autumn, the impact of hydroelectric power plants on the amount of electricity produced is small compared to the spring months. It is higher than in summer, but production still cannot meet the demand for electric vehicles in the evening hours and not even during the day. In total, the annual electricity production from hydroelectric power plants amounts to approximately 2.70 TWh/year, which almost corresponds to the required demand for EVs of 2.85 TWh/year. The production schedule of hydroelectric power plants varies depending on the schedules of charging profiles for electric cars, so their correlation is very minimal.

An important type of renewable energy projected in the modelling is the electricity produced by PV. In the calculations, their capacity in 2050 is planned to be about 500 MW. The amount of electricity produced during the day can to meet the electricity demand of EV users. In the evening hours, when the greatest peak demand is observed for the home charging profile, electricity imports are required. Based on modelling, it can be concluded that PV is an important source of energy to cover the energy demand generated by the transport sector during the summer period. In the winter months, WPP is considered to be the most important source, while in the spring and autumn period, it is characteristic that the availability of electricity produced by PV increases, slightly reducing the demand for energy required from WPPs and hydropower plants.

On the other hand, the results on the possible reduction of the average total cost of electricity distribution and the CO_2 emissions avoided were obtained assuming that the number of EVs increases from the current 1000 vehicles to 500 000 vehicles in 2050, which is based on the forecast of replacing light road transport with internal combustion engines with electric transport. With such a dynamic of EV development, the total electricity consumption in the system would increase by about 1.248 TWh/year, which is about 20 % of the current electricity consumption. Such an increase in electricity consumption contributes to additional revenues for the network operator, which in turn, after the deduction of eligible costs (mainly those related to the increase in electricity losses), can be used to reduce the average distribution tariff (EUR/kWh) by about 0.2 % per year. This corresponds to an economic benefit for all electricity consumers of approximately EUR 0.7 million/year. The results show (see Fig. 9) that the tariff reduction (average total cost of electricity distribution) is relatively small, i.e. 0.9 % in total, if the number of EVs increases from 1000 to 500 000. If the number of EVs doubles, the tariff decreases by 0.017 %.

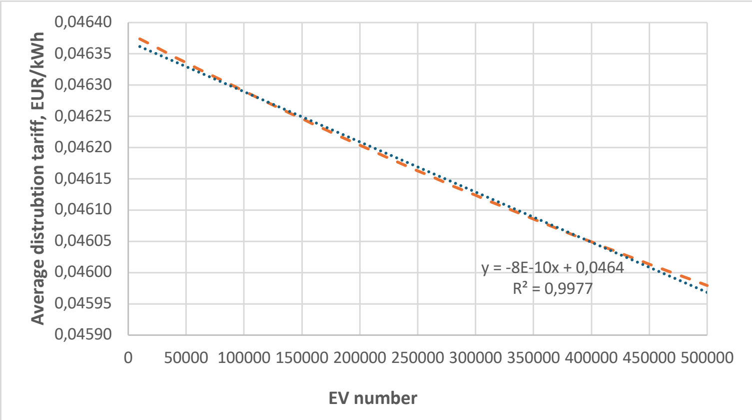


Fig. 9. Average distribution tariff depending on the number of EVs in Latvia.

A more significant environmental and socio-economic effect is achieved from the potential reduction of CO_2 emissions when EVs replace internal combustion engines using fossil fuels. When the number of EVs reaches 500 000, the avoided cost of CO_2 emissions (the cost that would have been incurred if allowances for CO_2 were to be purchased on the ETS emissions market), assuming a CO_2 price of 43 EUR/t (this level was reached by the end of March 2021) amounted to around EUR 45 million/year (see Fig. 10).

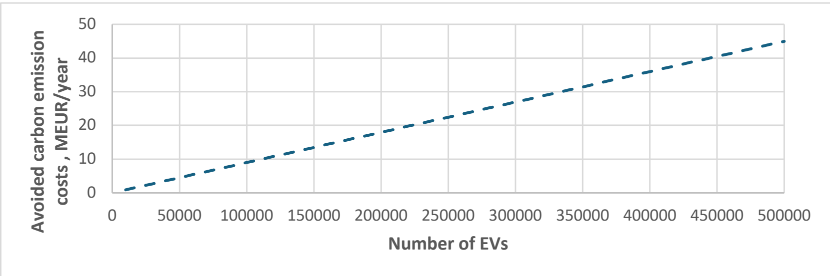


Fig 10. Avoided CO_2 emission costs depending on the number of EVs in Latvia.

In particular, each EV generates around 90 EUR/year cost of CO_2 emissions with an assumed CO_2 price or 2 t of CO_2 emissions per year. It should also be noted that such estimates are based on the approach that CO_2 emissions from fossil fuel-using cars are 200 g/km and thus reflect emissions throughout the life cycle of internal combustion engines. For EVs, the calculation is based on emissions related to the production of electricity consumed and is based on Latvia's average CO_2 emissions per kWh of electricity, i.e. approximately 200 g/kWh. This figure reflects a relatively conservative scenario, according to which approximately 40 % of electricity demand is met using fossil production sources and exceeds the historical average calculated CO_2 intensity for Latvia by about 65 %.

The results of the analysis of the benefits for individual EV users of using PV for the decarbonisation of transport reveal (Fig. 11) that, from the point of view of electricity costs, which include grid connection and electricity costs, as well as fuel costs, EVs provide significant savings compared to internal combustion engine cars. The use of electricity generated from PV for charging in accordance with the existing tariff system ensures an additional reduction in mobility costs. However, including the costs associated with the purchase of the vehicle and the associated maintenance costs and taxes, reduces the savings associated with the use of EVs and PV.

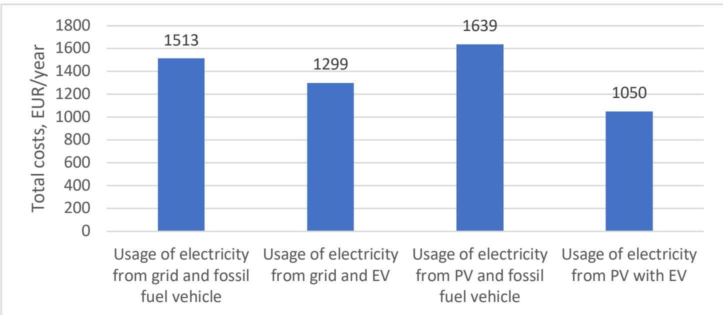


Fig. 11. Total annual energy costs of the scenarios.

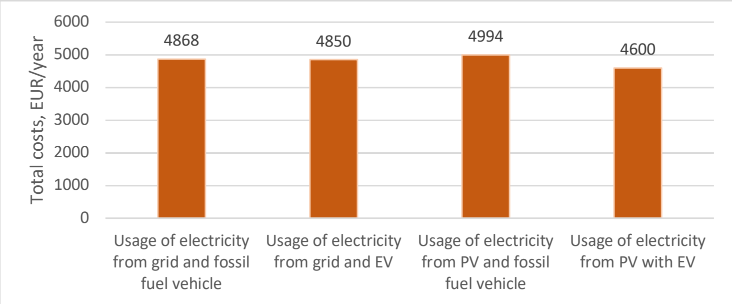


Fig. 12. Annual total cost in various scenarios, including the cost of purchasing vehicles (initial investment in the vehicle is depreciated over a 7-year period at an annual interest rate of 1.49 %) and taxes.

The analysis reveals that the main factors determining potential benefits are related to higher EV acquisition costs, which are partly offset by lower taxes, more favourable financing conditions, and lower maintenance and use costs. The analysis also reveals that while the main cost advantages are related to the overall efficiency of EVs, in the scenario of the use of electricity generated by PV to charge EVs, the cost advantages of electric mobility are also related to the network payment system. The actual structure of the formation of tariffs determines that the most economically advantageous for PV owners is a scenario in which the customer, with the help of PV, is able to produce as much electricity as possible for his own consumption without exceeding it. In this case, the main economic benefits for the solar user are that the user avoids unreasonably high investment costs associated with the initial purchase of equipment and reduces the variable costs associated with the purchase of electricity from the network. A comparison of the two scenarios with similar PV installed capacity reveals that a scenario where a household consumes all the electricity produced for its mobility needs instead of transferring part of it back to the grid is more economically advantageous for the customer and also improves the economic performance of PV. Meanwhile, as seen in Fig. 12, for PV with installed capacity that provides a production volume that significantly exceeds the user's own consumption, economic indicators under the existing tariff and tax framework may worsen the economic performance of PV (as seen in the scenario "Usage of electricity from PV and fossil fuel vehicle"), and this is due to an increase in the cost of network services.

From the preliminary analysis of the economic synergies between PV and electric cars, it is possible to identify a number of important circumstances that could potentially have a significant impact on the overall benefits or costs. In general, household electricity connections have a relatively low load; therefore, increasing electricity consumption in a given connection, in most cases, provides a greater economy by reducing costs per unit of energy consumed. It can also be concluded that the increase in electricity consumption due to the charging of EVs in a particular household, while maintaining a constant electricity connection capacity, has a positive economic impact on the unit cost of electricity consumed. At the same time, taking into account the scenario of PV installation at the user's facility, the load is reduced, and the share of costs related to the maintenance of the distribution connection capacity according to the tariff structure increases comparatively. However, when PV equipment replaces the amount of electricity purchased from the network, a number of other components of the final cost of electricity are reduced, including costs related to the distribution service.

3.2. Prospects for the decarbonisation of heavy transport through synthetic fuels

The decarbonisation of heavy transport through synthetic fuels takes into account the increase in capacity of RES and synthetic fuel production technologies, the technological feasibility of infrastructure and institutional aspects. The production capacity of ethanol, which has been assessed as one of the possible synthetic fuels in the framework of the study, is determined by two main factors – the amount of captured CO_2 emissions and the economic competitiveness of the production costs of the ethanol unit compared to the production costs of the alternative fuel unit. Both of these factors determine the investment in ethanol production capacity. The financing of research and development and direct subsidies for ethanol production increase the economic competitiveness of ethanol production. If the share of captured CO_2 emissions is increased from 15 % to 100 %, then ethanol production capacity increases by the same ratio, about 6.5 times, which could be expected. It is surprising that funding for R&D and subsidies has a relatively small impact on ethanol production capacity in the baseline scenario. The explanation is that the funding allocated to R&D exceeds the baseline funding and reduces the time needed for R&D compared to the case without this funding, i.e. the time at the base level. If the time at the R&D base level is small enough, ethanol production becomes economically competitive with the alternative quickly enough and reaches almost the same production capacity during the period in question without additional funding for research as is achieved with additional funding. This explanation can be verified if the "Research time for reducing unit costs" and "Development time for reducing unit costs" in the model are doubled to 10 and 6 years, respectively. These changes lead to a greater difference in ethanol production capacity dynamics when funding for R&D and subsidies is removed. It should be noted that if there is no R&D at all (the R&D time in the model is very large), the ethanol production technology is not competitive with the alternative and is not invested in production capacity.

As ethanol production capacity increases, so does the ethanol produced, which replaces fossil fuels in the transport sector. If the lowest heat of combustion (LHC) of fossil fuels is about 12 MWh/t and the LHC of ethanol is 7.42 MWh/t, then 1 t of ethanol replaces 0.62 tons of fossil fuel. If synthetic ethanol is assumed to be carbon neutral (because it is made from captured CO_2 and H_2 produced from renewable energy sources) and it is assumed that the CO_2 emission factor for fossil fuels is around 3.03 t CO_2/t of fuel, then each tonne of ethanol in the transport sector eliminates approximately 1.9 tonnes of CO_2. The results show that the share of CO_2 emissions avoided, i.e. the ratio of avoided CO_2 emissions from replacing fossil fuels with ethanol to the total CO_2 emissions in the transport sector as in 2020, corresponds to the same "S-shaped" increase as ethanol production capacity. An 80 % reduction in CO_2 emissions from transport could be achieved if 100 % of industrial CO_2 emissions could be used to produce synthetic fuels while the reference scenario would achieve a reduction of around 12 %. The share of synthetic fuels in the total final energy consumption in transport (if consumption were to remain at the level of 2020) in these two scenarios would be 74 % and 11 %, respectively.

The results of the sensitivity analysis show that the share of CO_2 emissions avoided in transport is most affected by the production costs of H_2, and the share decreases as H_2 costs increase. This result coincides with many other studies, which indicate that the production of alcohols by hydrogenation of CO_2 is economically viable only at a certain level of H_2 cost. This has been confirmed in a study looking at the use of a CoMoS catalyst for a reaction [38] [20], [39] [7], and a study looking at the technical-economic rationale for thermocatalytic CO_2 hydrogenation for methanol and ethanol production [37][4]. In order to assess the prospects for the production of synthetic fuels for heavy road transport in different scenarios of renewable energy production capacity, an analysis was carried out for each of the three scenarios used in the study.

Scenario 1 – Most Likely (Most Possible)

To produce 8.2 TWh of synthetic fuel, which is the amount of fuel demand identified in the modelling, 14.02 TWh of electricity is required for electrolysis. This would require a net import of electricity (the difference between imports and exports) of 8.835 TWh per year. Modelling confirms that the volume of electricity imported in the week of March is higher than the exported ones and only a few hours this week the production of electricity satisfies the demand, although it is known that March is a very good month for generating electricity, since the wind is quite strong and there is a large amount of water flowing through hydroelectric power plants in the rivers. If we take into account the import prices of electricity in 2021 (~ 80 EUR/MWh$_e$), then the import costs would be approximately 707 MEUR/year. In comparison, net imports of electricity into Latvia in 2021 amounted to 1.77 TWh$_e$.

Therefore, a second option was created for this scenario, assessing the amount of synthetic fuel that can be produced if net electricity imports remain at the same level as in 2021, i.e. 1.77 TWh$_e$ per year. The results show that such net imports of electricity could produce 3.6 TWh, or 44 % of the required amount of synthetic fuels, and would require 6.19 TWh$_e$ of electricity for electrolysis. The remaining 4.6 TWh of fuel in the heavy transport sector would be provided with fossil fuels that would be the same as in 2021, producing the same CO_2 emissions as in 2021. This suggests that the increase in renewable energy in this scenario is outweighed by the increase in fuel consumption in heavy-duty transport. This prevents an increase in annual CO_2 emissions but doesn't help to reduce it.

Scenario 2 – Maximum offshore wind energy

In order to reduce CO_2 emissions, it is necessary to increase the production capacity of renewable energy sources so that the system can produce an additional 8.835 TWh$_e$ for electrolysis, and to ensure the production of 8.2 TWh of synthetic fuel. When the capacity of the offshore WPP was changed, it was found that the capacity should be increased by 4765 MW. In such a scenario, net electricity imports would be zero. However, relatively high volumes of exports and imports remain at around 5.72 in both directions. This may not be economically viable as the import price could often be higher than the export price. In the model, the initially selected volume of hydrogen storage tanks is small, and the model uses electricity for electrolysis only as much as is necessary for transport needs at a given moment, converting the produced hydrogen into synthetic fuel and consuming it for transport purposes. If the volume and electrolysis capacity of hydrogen storage tanks were increased, all export capacity would be diverted to hydrogen production, preventing net imports of electricity. However, storing hydrogen in large quantities is complex and expensive, and these costs could exceed the difference between the import and export prices of electricity, so it would be more profitable to build synthetic fuel storage tanks. Such a solution is tested in Scenario 3.

Scenario 3 – Storage of synthetic fuels

If we take the electricity generation capacity of Scenario 1 as a basis, then it should be possible to store 10.64 TWh of hydrogen, since this amount is necessary for the production of 8.2 TWh of synthetic fuel. Of this volume, 4.18 TWh consists of DME, which replaces diesel fuel for storage, and its storage requires a volume of 789 thou. m^3, 3.99 TWh for storage of aviation e-kerosene – 433 thou. m^3, but for ammonia, which is used in ship transport – 9.5 thous. m^3.

In such a scenario, imports and exports would be the same – 0.73 TWh per year. The added synthetic fuel storage tanks make it possible to reduce the volume of cross-border flows of electricity, providing that electrolysis plants are operated only at times when there is a surplus of electricity generation from WPP, which was one of the main conditions in the production of synthetic fuels.

3.3. Analysis of the impact of RES production sources on electricity market developments and the decarbonisation of transport

Electricity prices are one of the most important cost items both in the operation of EVs and in the production of synthetic fuels; therefore, long-term price predictability is an important factor in identifying the investments to be made in these activities and ensuring predictability for them, while also justifying investments in electricity generation capacities. A comparison of the statistics obtained on the Nord Pool stock exchange shows that in the short term, which lasts one week, there is a significant correlation between the production of electricity from wind power plants and prices. For the analysis, two 7-day periods in 2019, from 1 November to 7 November and from 3 December to 9 December , were selected for comparison for the following reasons: total electricity consumption, number of working days, ambient air temperature, and the number of restrictions related to the availability of production facilities were mostly similar in both periods, and the availability of the hydro reserves (characterized by the fact that in both periods it exceeded the long-term median value in the corresponding week of the year) was high during the analysis period considered. Meanwhile, according to calculations, the difference in the volume of wind electricity production between the scenarios exceeded 100 %. Thus, the only significant variable in both periods of analysis was the volume of wind electricity generation. The calculation confirmed that the average price difference between the scenarios was around 13 %, which can be considered significant. However, this suggests that during longer analysis periods, the electricity produced by wind power plants has a much smaller impact on fluctuations in electricity prices than in shorter periods, which sometimes experienced price differences of up to 100 % in 24-hour periods on one day and constant differences of up to 25 % in 24-hour periods.

An analysis of the data on an annual basis confirms that, despite strong short-term fluctuations associated with changes in wind energy production, there is no significant correlation between electricity prices and wind power production over a longer period (. Nord Pool markets reacted to the very large volumes of wind energy produced (MWh) with relatively moderate price fluctuations, and no significant impact can be observed in periods with a very low share of wind energy. Meanwhile, most cases where the wholesale price of electricity significantly exceeded or was below the average level were recorded during periods when wind energy production was average, ranging from 40 000 MWh to 100 000 MWh per day in the regions of Finland, Denmark and the Baltic States. Similar results were observed for hourly analyses in the Baltic region and Denmark (see Figs. 13 and 14).

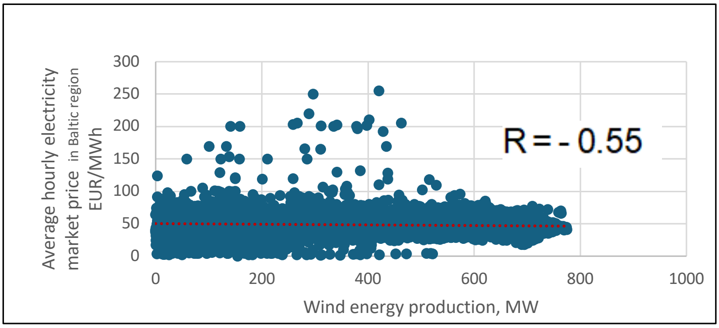


Fig. 13. Relation between wind energy production and hourly electricity market price in the Baltic region in 2019 (data source: Nord Pool).

Although the data show that the correlation between the volume and price of wind electricity production in Denmark is higher than in the Baltic States, the correlation in both regions is very low (Fig. 14).

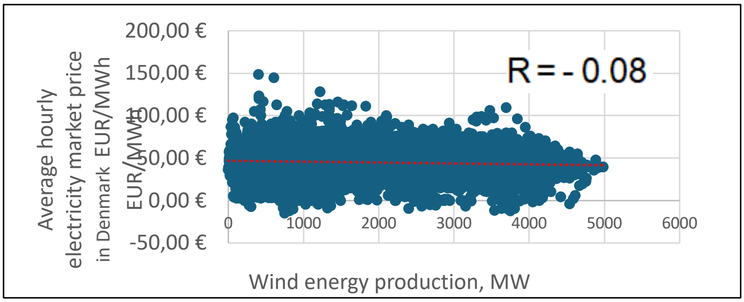


Fig. 14. Relation between wind energy production and the market price of electricity at an hourly rate in Denmark in 2019 (data source: Nord Pool).

Identical observations can be made for the correlation between the share of wind energy in the total final electricity consumption and hourly electricity prices in both Denmark and the Baltic States. In both cases, the correlation was higher than in the scenario with wind power generation, but it is still very low. In addition, analysis of electricity consumption data showed that the wholesale price of electricity has a much stronger positive correlation with electricity consumption (Fig. 15).

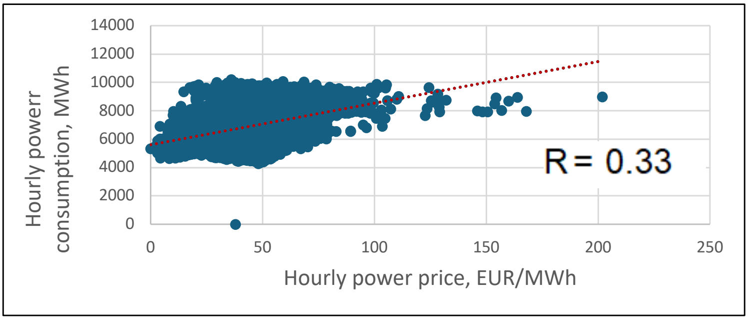


Fig. 15. Correlation between electricity market price and hourly electricity consumption in 2019 (data source: Nord Pool, 2020).

In order to assess the impact of fluctuations in electricity market prices caused by intermittent wind energy production on the economic performance of Danish wind energy producers in 2019, the weighted average price per MWh of wind energy sold by Nord Pool was calculated and compared with the weighted average trading price.

Calculations show that in 2019, wind electricity producers sold the electricity produced by WPP at a weighted average price of EUR 44.27 per MWh, while the weighted average market price was EUR 44243.96 per MWh. Thus, the price difference is about 0.7 %, which suggests that the income of wind energy producers is only insignificantly affected by the price decrease during periods with a large share of electricity produced by WPP, and, on the contrary, in general, the revenues of producers for electricity sold on the market per MWh are slightly higher than the market average.

4. CONCLUSIONS

- The results of a study assessing the amount of electricity that can be produced by solar PV installed at gas stations and intended for charging EVs show that solar PV cells at gas stations can provide about 2 % of the total electricity needed to charge EVs in Latvia. PV installed in other charging facilities outside service stations, i.e. in public charging points, could provide around 14 % of the electricity needed to charge EVs.
- The speed of replacing the FV fleet with EVs is the most crucial factor in reducing CO_2 emissions in the transport sector. The biggest influence on the growth rate of EVs is the difference between the prices of new EVs and FVs. The two main mechanisms that reduce the price difference between EVs and FVs are a reduction in the price of EVs as a result of technological developments and direct subsidies for the purchase of EVs. Thus, direct subsidies for the purchase of EVs could be the most effective policy instrument to support the decarbonisation and electrification of transport. Policy instruments should incentivise the transition from FV to EVs as early as possible. The energy source used to charge EVs is of secondary importance in relation to cumulative CO_2 emissions in the transport sector.
- An analysis of the potential impact of the development of light EVs on the electrical load profile concluded that in the fast charging scenario, peak hours were more pronounced in the middle of the day, while in the home charging scenario, peak hours were only in the evening hours. In the home charging scenario, evening peaks were much higher, and the daytime charging profile was more uneven. For fast charging stations, the profile was much smoother during the day, with smaller peaks.
- According to the seasons, higher electricity demand from EV users is observed during the warm months of the year, when the population moves more. The electricity produced by WPP in winter, hydropower plants in spring and solar PV in summer helps to steadily meet the demand for electricity from charging stations during most time periods. The biggest problems with the load on the electrical network can be seen in the evening hours when there is not enough development of WPP, and there is no longer access to solar PV electricity. The peak hours for EV charging are often in the evening

hours, thus necessitating the import of electricity that cannot be covered by renewable energy sources.

- At the same time, the assessment of the potential load and energy consumption caused by EVs confirms that the installed capacity of the Latvian electricity grid is sufficient to meet the EV charging needs even if the entire fleet of fossil vehicles is replaced by EVs. Therefore, there is no evidence that the electrification of road transport requires significant additional investments in the power grid. Calculations also suggest that a possible increase in electricity demand would benefit network operators and create an additional income stream that can be used to reduce the network charge per unit of electricity supplied.
- The direct economic benefit associated with more intensive use of the electricity grid can be described as relatively insignificant at around 0.2 % or 0.7 million EUR/year when the penetration of EVs reaches around 500 000 units. Meanwhile, the value of CO_2 emissions avoided is more significant and can reach around 45 million EUR/year, when the penetration of EVs reaches around 500 000 units.
- Analysis of the synergy of electric cars and household PV indicates that the costs associated with the purchase of both solar energy equipment and vehicles are one of the most important cost-determining factors for the economic indicators of both technologies. In addition to the direct economic advantages, synergies between the two technologies also have great potential to reduce fluctuations in energy costs.
- Drawing on the findings of studies on the use of synthetic fuels in the decarbonisation of heavy transport, it can be concluded that by 2050 it is possible to decarbonise the heavy transport sector by using electricity produced from renewable energy sources, producing synthetic fuels and storing them in large volumes.
- If passenger transport is to be decarbonised through electric motors, which also require electricity produced from renewable energy sources, then additional renewable electricity capacity should be installed.
- The results also indicate that the projected maximum electrical load is likely to significantly exceed the capacity of existing transmission and distribution networks and thus justify the need for further studies to assess the costs of a strategy for decarbonising

transport through synthetic fuels in relation to the expansion and adaptation of existing electricity grids.

The results of the study on the potential of synthetic fuels in the heavy transport sector and its dependence on institutional factors show that the costs of hydrogen production and CO_2 capture (the difference between capture costs and the price of CO_2 emissions), as well as specific capital investments in the production capacity (technology costs) of synthetic fuels (modelling for ethanol production), are three of the most important factors determining the result of the modelled systems. The cost of hydrogen production has the greatest impact on the evolution of ethanol production capacity and the resulting avoided CO_2 emissions in the transport sector. A 1 % increase in the cost of hydrogen production reduces the amount of CO_2 emissions avoided in the transport sector by 0.32 %.

The results show that using the money saved thanks to the CO_2 emissions avoided to develop synthetic fuel production technologies creates a multiplier effect that avoids even greater CO_2 emissions in the future. As the results show, technological development and research are essential for the development of the production of synthetic fuels from captured CO_2, and without funding for these needs, technological development is unlikely.

Summing up the most important results from the study conducted on the impact of the development of electricity capacities on the market and total consumer costs in the long term, it should be noted that all the modelled scenarios confirmed the economic and technical feasibility of further increasing the installed renewable energy capacity, in particular wind and PV energy sources. Moreover, in all scenarios, annual costs for energy consumers are expected to be at a significantly lower level than in reference year 2017. Scenarios involving more intensive support to promote the development of RES as well as incentives to improve energy efficiency result in a relatively higher annual cost burden but lower costs per unit of energy consumed in the future than in the reference year.

The analysis also showed that given the range of available energy storage technologies, of which pumped storage power plants and battery batteries are considered to be the most important technologies, the storage capacity for a full balancing of the electricity produced by WPP and solar PV may not be sufficient. In this context, other energy storage options should be explored, such as the use of underground storage facilities for the storage of synthetic gas or biomethane, as well as hydrogen storage, considering the need to preserve existing natural gas infrastructure.

On the other hand, when analysing the impact of renewable energy production plants on the dynamics of electricity market prices by year and hour, the results did not show a correlation between the share of electricity produced by WPP and the market price of electricity. The value of R was only −0.15 for Denmark, which is the country with the highest distribution of wind energy in the Nordic and Baltic regions, and similarly low ($R = -0.15$) for the Baltic states. Therefore, it was not possible to obtain any functional relationship between the increase in the share of wind energy and the resulting reduction in the market price of electricity, which could be used in future modelling of energy systems. However, these observations also indicated that the impact of volatile renewable energy sources, such as wind energy, on electricity market prices is lower over the longer term than previously thought and generally does not pose significant risks to long-term wholesale price stability and a decline in investor interest.

5. REFERENCES

[1] European Environment Agency, "Greenhouse gas emissions from transport in Europe." Accessed: Feb. 02, 2024. [Online]. Available: https://www.eea.europa.eu/ims/greenhouse-gas-emissions-from-transport

[2] EUROCONTROL, "EUROCONTROL Forecast Update 2022–2024," Accessed: Feb. 02, 2024. [Online]. Available: https://www.euroCOntrol.int/publication/euroCOntrol-forecast-update-2022-2024

[3] G. P. Peters, G. Marland, C. Le Quéré, T. Boden, J. G. Canadell, and M. R. Raupach, "Rapid growth in CO 2 emissions after the 2008–2009 global financial crisis," *Nat. Clim. Chang.*, vol. 2, no. 1, pp. 2–4, Jan. 2012, doi: 10.1038/NCLIMATE1332.

[4] R. Figueiredo, P. Nunes, and M. C. Brito, "The feasibility of solar parking lots for electric vehicles," *Energy*, vol. 140, pp. 1182–1197, Dec. 2017, doi: 10.1016/J.ENERGY.2017.09.024.

[5] P. D. dos Santos, A. C. Zambroni de Souza, B. D. Bonatto, T. P. Mendes, J. A. S. Neto, and A. C. B. Botan, "Analysis of solar and wind energy installations at electric vehicle charging stations in a region in Brazil and their impact on pricing using an optimized sale price model," *Int. J. Energy Res.*, vol. 45, no. 5, pp. 6745–6764, Apr. 2021, doi: 10.1002/ER.6269.

[6] M. T. Turan and E. Gökalp, "Integration Analysis of Electric Vehicle Charging Station Equipped with Solar Power Plant to Distribution Network and Protection System Design," *Journal of Electrical Engineering and Technology*, vol. 17, no. 2, pp. 903–912, Mar. 2022, doi: 10.1007/S42835-021-00927-X.

[7] Nityanshi, T. Mathur, V. A. Tikkiwal, and K. Nigam, "Feasibility analysis of a solar-assisted electric vehicle charging station model considering differential pricing," *Energy Storage*, vol. 3, no. 4, Aug. 2021, doi: 10.1002/EST2.237.

[8] D. Yan and C. Ma, "Stochastic planning of electric vehicle charging station integrated with photovoltaic and battery systems," *IET Generation, Transmission and Distribution*, vol. 14, no. 19, pp. 4217–4224, Oct. 2020, doi: 10.1049/IET-GTD.2019.1737.

[9] C. Filote, R. A. Felseghi, M. S. Raboaca, and I. Aşchilean, "Environmental impact assessment of green energy systems for power supply of electric vehicle charging station," *Int. J. Energy Res.*, vol. 44, no. 13, pp. 10471–10494, Oct. 2020, doi: 10.1002/ER.5678.

[10] M. A. Tamor and E. B. Stechel, "Electrification of transportation means a lot more than a lot more electric vehicles," *iScience*, vol. 25, no. 6, p. 104376, Jun. 2022, doi: 10.1016/J.ISCI.2022.104376.

[11] Q. Hu, H. Li, and S. Bu, "The Prediction of Electric Vehicles Load Profiles Considering Stochastic Charging and Discharging Behavior and Their Impact Assessment on a Real UK Distribution Network," *Energy Procedia*, vol. 158, pp. 6458–6465, Feb. 2019, doi: 10.1016/J.EGYPRO.2019.01.134.

[12] M. Yuan, J. Z. Thellufsen, H. Lund, and Y. Liang, "The electrification of transportation in energy transition," *Energy*, vol. 236, p. 121564, Dec. 2021, doi: 10.1016/J.ENERGY.2021.121564.

[13] A. Sadri, M. M. Ardehali, and K. Amirnekooei, "General procedure for long-term energy-environmental planning for transportation sector of developing countries with limited data based on

LEAP (long-range energy alternative planning) and EnergyPLAN," *Energy*, vol. 77, pp. 831–843, Dec. 2014, doi: 10.1016/J.ENERGY.2014.09.067.

[14] L. Udrene and G. Bazbauers, "Role of Vehicle-to-grid Systems for Electric Load Shifting and Integration of Intermittent Sources in Latvian Power System," *Energy Procedia*, vol. 72, pp. 156–162, Jun. 2015, doi: 10.1016/J.EGYPRO.2015.06.022.

[15] W. You *et al.*, "Technical and economic assessment of RES penetration by modelling China's existing energy system," *Energy*, vol. 165, pp. 900–910, Dec. 2018, doi: 10.1016/J.ENERGY.2018.10.043.

[16] W. Liu, H. Lund, B. V. Mathiesen, and X. Zhang, "Potential of renewable energy systems in China," *Appl Energy*, vol. 88, no. 2, pp. 518–525, Feb. 2011, doi: 10.1016/J.APENERGY.2010.07.014.

[17] H. Lund, J. Z. Thellufsen, P. A. Østergaard, P. Sorknæs, I. R. Skov, and B. V. Mathiesen, "EnergyPLAN – Advanced analysis of smart energy systems," *Smart Energy*, vol. 1, Feb. 2021, doi: 10.1016/j.segy.2021.100007.

[18] M. Z. Jacobson *et al.*, "100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World," *Joule*, vol. 1, no. 1, pp. 108–121, Sep. 2017, doi: 10.1016/J.JOULE.2017.07.005.

[19] D. Connolly, H. Lund, B. V. Mathiesen, E. Pican, and M. Leahy, "The technical and economic implications of integrating fluctuating renewable energy using energy storage," *Renew Energy*, vol. 43, pp. 47–60, Jul. 2012, doi: 10.1016/J.RENENE.2011.11.003.

[20] D. Connolly, "The Integration of Fluctuating Renewable Energy Using Energy Storage," University of Limerick, Limerick, 2010. Accessed: Feb. 19, 2024. [Online]. Available: https://vbn.aau.dk/files/549485799/David_Connolly_PhD_2010_Updated_Journal_Appendices_2012_.pdf

[21] F. A. Farret and M. Godoy. Simões, "Integration of alternative sources of energy," p. 471, 2006.

[22] H. Lund *et al.*, "Energy storage and smart energy systems," *International Journal of Sustainable Energy Planning and Management*, vol. 11, pp. 3–14, 2016, doi: 10.5278/IJSEPM.2016.11.2.

[23] S. Djørup, J. Z. Thellufsen, and P. Sorknæs, "The electricity market in a renewable energy system," *Energy*, vol. 162, pp. 148–157, Nov. 2018, doi: 10.1016/J.ENERGY.2018.07.100.

[24] B. Ćosić, G. Krajačić, and N. Duić, "A 100 % renewable energy system in the year 2050: The case of Macedonia," *Energy*, vol. 48, no. 1, pp. 80–87, Dec. 2012, doi: 10.1016/J.ENERGY.2012.06.078.

[25] J. Porubova and G. Bazbauers, "Analysis of Long-Term Plan for Energy Supply System for Latvia that is 100 % Based on the Use of Local Energy Resources," *Environmental and Climate Technologies*, vol. 4, no. 1, pp. 82–90, 2010, doi: 10.2478/V10145-010-0022-7.

[26] J. De Hoog *et al.*, "Electric vehicle charging and grid constraints: Comparing distributed and centralized approaches," *IEEE Power and Energy Society General Meeting*, 2013, doi: 10.1109/PESMG.2013.6672222.

[27] L. Held *et al.*, "The influence of electric vehicle charging on low voltage grids with characteristics typical for Germany," *World Electric Vehicle Journal*, vol. 10, no. 4, Dec. 2019, doi: 10.3390/WEVJ10040088.

[28] T. Bräunl, D. Harries, M. McHenry, and G. Wager, "Determining the optimal electric vehicle DC-charging infrastructure for Western Australia," *Transp. Res. D. Transp. Environ.*, vol. 84, p. 102250, Jul. 2020, doi: 10.1016/J.TRD.2020.102250.

[29] C. D. White and K. M. Zhang, "Using vehicle-to-grid technology for frequency regulation and peak-load reduction," *J. Power Sources*, vol. 196, no. 8, pp. 3972–3980, Apr. 2011, doi: 10.1016/j.jpowsour.2010.11.010.

[30] S. Deilami, A. S. Masoum, P. S. Moses, and M. A. S. Masoum, "Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile," *IEEE Trans Smart Grid*, vol. 2, no. 3, pp. 456–467, Sep. 2011, doi: 10.1109/TSG.2011.2159816.

[31] G. Cardoso *et al.*, "Optimal investment and scheduling of distributed energy resources with uncertainty in electric vehicle driving schedules," *Energy*, vol. 64, pp. 17–30, Jan. 2014, doi: 10.1016/j.energy.2013.10.092.

[32] A. Foley, B. Tyther, P. Calnan, and B. Ó Gallachóir, "Impacts of Electric Vehicle charging under electricity market operations," *Appl. Energy*, vol. 101, pp. 93–102, 2013, doi: 10.1016/j.apenergy.2012.06.052.

[33] I. Staltmanis, *Latvijas Enerģētika Ceļā Uz Patstāvību*. Riga: AS "Latvenergo", Latvijas enerģētiķu un elektrotehniķu zinātniski tehniskā biedrība, 1992.

[34] P. Nunes, M. C. Brito, and T. Farias, "Synergies between electric vehicles and solar electricity penetrations in Portugal," *World Electric Vehicle Journal*, vol. 6, no. 4, pp. 1151–1158, 2013, doi: 10.3390/WEVJ6041151.

[35] H. Tidey and S. Lyden, "Coordination of electric vehicle battery charging with photovoltaic generation," *2017 Australasian Universities Power Engineering Conference, AUPEC 2017*, vol. 2017–November, pp. 1–6, Feb. 2018, doi: 10.1109/AUPEC.2017.8282453.

[36] D. B. Richardson, "Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration," *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 247–254, Mar. 2013, doi: 10.1016/J.RSER.2012.11.042.

[37] C. Camus and T. Farias, "The electric vehicles as a mean to reduce CO 2 emissions and energy costs in isolated regions. The São Miguel (Azores) case study," *Energy Policy*, vol. 43, pp. 153–165, Apr. 2012, doi: 10.1016/j.enpol.2011.12.046.

[38] E. S. Amundsen and L. Bergman, "Why has the Nordic electricity market worked so well?" *Util. Policy*, vol. 14, no. 3, pp. 148–157, Sep. 2006, doi: 10.1016/J.JUP.2006.01.001.

[39] Ministru kabinets, "Atviegloti nosacījumi neto sistēmas lietotājiem." Accessed: Feb. 18, 2024. [Online]. Available: https://www.mk.gov.lv/lv/jaunums/atviegloti-nosacijumi-neto-sistemas-lietotajiem

[40] S. Hänggi *et al.*, "A review of synthetic fuels for passenger vehicles," *Energy Reports*, vol. 5, pp. 555–569, 2019, doi: 10.1016/j.egyr.2019.04.007.

[41] I. Ghiat and T. Al-Ansari, "A review of carbon capture and utilisation as a CO_2 abatement opportunity within the EWF nexus," *Journal of CO2 Utilization*, vol. 45, no. December 2020, p. 101432, 2021, doi: 10.1016/j.jcou.2020.101432.

[42] K. Atsonios, K. D. Panopoulos, and E. Kakaras, "Thermocatalytic CO_2 hydrogenation for methanol and ethanol production: Process improvements," *Int. J. Hydrogen Energy*, vol. 41, no. 2, pp. 792–806, 2016, doi: 10.1016/j.ijhydene.2015.12.001.

[43] K. Arning, A. Linzenich, L. Engelmann, and M. Ziefle, "More green or less black? How benefit perceptions of CO_2 reductions vs. fossil resource savings shape the acceptance of CO2-based fuels and

their conversion technology," *Energy and Climate Change*, vol. 2, no. May 2020, p. 100025, 2021, doi: 10.1016/j.egycc.2021.100025.

[44] Y. M. Alshammari, "Scenario analysis for energy transition in the chemical industry: An industrial case study in Saudi Arabia," *Energy Policy*, vol. 150, no. February 2020, p. 112128, 2021, doi: 10.1016/j.enpol.2020.112128.

[45] X. Chen, X. Wu, and K. Y. Lee, "The mutual benefits of renewables and carbon capture: Achieved by an artificial intelligent scheduling strategy," *Energy Convers. Manag.*, vol. 233, p. 113856, 2021, doi: 10.1016/j.enconman.2021.113856.

[46] G. Zang, P. Sun, A. A. Elgowainy, A. Bafana, and M. Wang, "Performance and cost analysis of liquid fuel production from H2and CO_2-based on the Fischer-Tropsch process," *Journal of CO2 Utilization*, vol. 46, no. February, p. 101459, 2021, doi: 10.1016/j.jcou.2021.101459.

[47] J. Hu, R. Harmsen, W. Crijns-Graus, E. Worrell, and M. van den Broek, "Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: A literature review of market design," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 2181–2195, Jan. 2018, doi: 10.1016/J.RSER.2017.06.028.

[48] D. Newbery, M. G. Pollitt, R. A. Ritz, and W. Strielkowski, "Market design for a high-renewables European electricity system," *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 695–707, Aug. 2018, doi: 10.1016/J.RSER.2018.04.025.

[49] IEA, "Renewables 2019 – Analysis." Accessed: Feb. 14, 2024. [Online]. Available: https://www.iea.org/reports/renewables-2019#overview

[50] Nordic Energy Research, "Baltic Energy Technology Scenarios 2018." Accessed: Feb. 14, 2024. [Online]. Available: https://www.nordicenergy.org/project/bente/

[51] IEA, "How will the electricity market of the future work? – Analysis " Accessed: Feb. 14, 2024. [Online]. Available: https://www.iea.org/commentaries/how-will-the-electricity-market-of-the-future-work

[52] Clerici, A., Cova, B., & Callegari, G. "Decarbonization of the electrical power sector in Europe: an asset, an opportunity or a problem? ." Accessed: Feb. 14, 2024. [Online]. Available: https://www.jstor.org/stable/43735343

[53] WindEurope, "Wind energy in Europe in 2019" Accessed: Feb. 14, 2024. [Online]. Available: https://windeurope.org/about-wind/statistics/european/wind-energy-in-europe-in-2019/

[54] WindEurope, "Wind in power: 2010 European statistics." Accessed: Feb. 14, 2024. [Online]. Available: https://windeurope.org/about-wind/statistics/european/wind-in-power-2010/

[55] W. Hu, Z. Chen, and B. Bak-Jensen, "The relationship between electricity price and wind power generation in Danish electricity markets," *Asia-Pacific Power and Energy Engineering Conference, APPEEC*, 2010, doi: 10.1109/APPEEC.2010.5448739.

[56] S. Pilpola and P. D. Lund, "Different flexibility options for better system integration of wind power," *Energy Strategy Reviews*, vol. 26, p. 100368, Nov. 2019, doi: 10.1016/J.ESR.2019.100368.

[57] Y. Li, "Quantifying the impacts of wind power generation in the day-ahead market: The case of Denmark".

[58] J. M. Roldan Fernandez, M. Burgos Payan, and J. M. Riquelme Santos, “The Merit-Order Effect of Load-Shifting: An Estimate for the Spanish Market,” *Environmental and Climate Technologies*, vol. 24, no. 1, pp. 43–57, Jan. 2020, doi: 10.2478/RTUECT-2020-0003.

[59] X. Li, “The impact of wind power generation on the wholesale electricity price Evidence from the Swedish electricity market,” 2017.

[60] E. A. Unger, G. F. Ulfarsson, S. M. Gardarsson, and T. Matthiasson, “The effect of wind energy production on cross-border electricity pricing: The case of western Denmark in the Nord Pool market,” *Econ. Anal. Policy*, vol. 58, pp. 121–130, Jun. 2018, doi: 10.1016/J.EAP.2018.01.006.

[61] E. Denny *et al.*, “The impact of increased interconnection on electricity systems with large penetrations of wind generation: A case study of Ireland and Great Britain,” *Energy Policy*, vol. 38, no. 11, pp. 6946–6954, Nov. 2010, doi: 10.1016/J.ENPOL.2010.07.011.

[62] W. You *et al.*, “Technical and economic assessment of RES penetration by modelling China’s existing energy system,” *Energy*, vol. 165, pp. 900–910, Dec. 2018, doi: 10.1016/J.ENERGY.2018.10.043.

[63] C. Byers, T. Levin, and A. Botterud, “Capacity market design and renewable energy: Performance incentives, qualifying capacity, and demand curves,” *The Electricity Journal*, vol. 31, no. 1, pp. 65–74, Jan. 2018, doi: 10.1016/J.TEJ.2018.01.006.

[64] G. Shrimali, S. Srinivasan, S. Goel, and D. Nelson, “The effectiveness of federal renewable policies in India,” *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 538–550, Apr. 2017, doi: 10.1016/J.RSER.2016.10.075.

[65] D. Yan and C. Ma, “Stochastic planning of electric vehicle charging station integrated with photovoltaic and battery systems,” *IET Generation, Transmission and Distribution*, vol. 14, no. 19, pp. 4217–4224, Oct. 2020, doi: 10.1049/IET-GTD.2019.1737.

[66] C. Filote, R. A. Felseghi, M. S. Raboaca, and I. Așchilean, “Environmental impact assessment of green energy systems for power supply of electric vehicle charging station,” *Int. J. Energy Res.*, vol. 44, no. 13, pp. 10471–10494, Oct. 2020, doi: 10.1002/ER.5678.

[67] ISEE, “STELLA Architect,” *Products*. p. 2021, 2016.

[68] Vides aizsardzības un reģionālās attīstības ministrija, “Elektromobiļi,” 2021.

[69] Volkswagen, “WW vehicle price.pdf.” [Online]. Available: https://www.volkswagen.co.uk/en/new.html

[70] CSDD, “Reģistrēto transportlīdzekļu skaits | Transportlīdzekļi | Statistika | CSDD.” 2020.

[71] The European Parliament and the Council, “EUR-Lex - 32014L0094 - EN - EUR-Lex,” *EU Directive Directive 2014/94/EU*. p. 20, 2014.

[72] IEA, “Projected Costs of Generating Electricity 2020 – Analysis,” 2021.

[73] Danish Energy Agency and Energinet, “Technology Data – Energy Plants for Electricity and District heating generation,” no. 36, p. 414, 2020.

[74] Latvenergo, “Elektroenerģijas cena.” [Online]. Available: https://latvenergo.lv/lv/jaunumi/elektroenergijas-cena/4

[75] Vides aizsardzības un reģionālās attīstības ministrija, “Siltumnīcefekta gāzu emisiju aprēķina metodika.”

[76] D. Bosseboeuf, B. Lapillone, M. Rousselot, and L. Sudries, “Sectoral Profile – Transport,” no. 1, pp. 1–8, 2021.

[77] CSDD, "Reģistrēto transportalīdzekļu sadalījums pēc degvielas veida." [Online]. Available: https://www.csdd.lv/transportlidzekli/transportlidzekli-vizualizacija

[78] Ceļu satiksmes drošības direkcija, "Average CO_2 emissions for vehicle."

[79] CSDD, "Reģistrēto transportlīdzekļu skaits | Transportlīdzekļi | Statistika ." Accessed: Jan. 25, 2023. [Online]. Available: https://www.csdd.lv/transportlidzekli/registreto-transportlidzeklu-skait

[80] CSDD, "Tehniskajā apskatē pērn vidēji 13 auto dienā atteica bremzes | Jaunumi." Accessed: Dec. 30, 2022. [Online]. Available: https://www.csdd.lv/jaunumi/csdd-tehniskaja-apskate-pern-videji-13-auto-diena-atteica-bremzes

[81] "Energy consumption of full electric vehicles cheatsheet – EV Database." Accessed: Feb. 07, 2023. [Online]. Available: https://ev-database.org/cheatsheet/energy-consumption-electric-car

[82] V. Síťař, T. Vysloužil, L. Raková, and T. Hruška, "The Power Load Model for Electric Vehicle Charging Modelling and its Utilisation for Voltage Level Studies and Cables Ampacity in Distribution Grid," *Manufacturing Technology*, vol. 21, no. 1, pp. 132–140, 2021, doi: 10.21062/MFT.2021.015.

[83] F. M. Andersen, H. K. Jacobsen, and P. A. Gunkel, "Hourly charging profiles for electric vehicles and their effect on the aggregated consumption profile in Denmark," *International Journal of Electrical Power and Energy Systems*, vol. 130, Sep. 2021, doi: 10.1016/J.IJEPES.2021.106900.

[84] "Uzlādes staciju tīkls e-mobi." Accessed: Feb. 19, 2024. [Online]. Available: http://www.e-transports.org/index.php/arhivs/e-mobi-uzlades-tikls

[85] "Uzlādes staciju tīkls e-mobi." Accessed: Dec. 30, 2022. [Online]. Available: http://www.e-transports.org/index.php/arhivs/e-mobi-uzlades-tikls

[86] "Latvijā atvērusies Ionity uzlādes stacija – Uzlādēts." Accessed: Mar. 19, 2023. [Online]. Available: https://uzladets.lv/latvija-atverusies-ionity-uzlades-stacija/

[87] "Medijiem | VIRŠI." Accessed: Mar. 19, 2023. [Online]. Available: https://www.virsi.lv/lv/par-mums/medijiem/AS-Virsi-A-attistis-elektrouzlades-tiklu-20-stacijas-visa-Latvija

[88] "IKEA atklāj bezmaksas uzlādes vietas elektroautomobiļiem | Kursors.lv." Accessed: Mar. 19, 2023. [Online]. Available: https://kursors.lv/2019/09/05/ikea-atklaj-bezmaksas-uzlades-vietas-elektroautomobiliem/

[89] "Volkswagen We Charge serviss – vai tiešām šajā dzīvē ir arī kaut kas lētāks? | Kursors.lv." Accessed: Mar. 19, 2023. [Online]. Available: https://kursors.lv/2022/11/29/volkswagen-we-charge-serviss-vai-tiesam-saja-dzive-ir-ari-kaut-kas-letaks/

[90] "Elektrum." Accessed: Mar. 19, 2023. [Online]. Available: https://elektrumveikals.lv/lv/uznemumam/elektroauto-uzlade/elektrum-uzlades-stacijas

[91] "Par 2021. Gada 4. ceturksnī reģistrētajiem elektrotransportlīdzekļiem." Accessed: Feb. 07, 2023. [Online]. Available: http://www.e-transports.org/index.php/statistika/33-elektro-transportlidzekli/333-par-2021-gada-4-ceturksni-registretajiem-elektrotransportlidzekliem

[92] S. Á. Funke, F. Sprei, T. Gnann, and P. Plötz, "How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison," *Transp. Res. Part D: Transp. Environ.*, vol. 77, pp. 224–242, Dec. 2019, doi: 10.1016/j.trd.2019.10.024.

[93] M. Muratori, D. Greene, E. Kontou, and J. Dong, "The role of infrastructure to enable and support electric drive vehicles: A Transportation Research Part D Special Issue," *Transportation Research Part D: Transport and Environment*, vol. 89. Elsevier Ltd, p. 102609, Dec. 01, 2020. doi: 10.1016/j.trd.2020.102609.

[94] M. Baresch and S. Moser, "Allocation of e-car charging: Assessing the utilization of charging infrastructures by location," *Transp. Res. Part A: Policy Pract.*, vol. 124, pp. 388–395, Jun. 2019, doi: 10.1016/j.tra.2019.04.009.

[95] A. Miele, J. Axsen, M. Wolinetz, E. Maine, and Z. Long, "The role of charging and refuelling infrastructure in supporting zero-emission vehicle sales," *Transp. Res. Part D: Transp. Environ.*, vol. 81, p. 102275, Apr. 2020, doi: 10.1016/j.trd.2020.102275.

[96] B. C. Clinton and D. C. Steinberg, "Providing the Spark: Impact of financial incentives on battery electric vehicle adoption," *J. Environ. Econ. Manage.*, vol. 98, p. 102255, Nov. 2019, doi: 10.1016/J.JEEM.2019.102255.

[97] B. C. Clinton and D. C. Steinberg, "Providing the Spark: Impact of financial incentives on battery electric vehicle adoption," *J. Environ. Econ. Management*, vol. 98, Nov. 2019, doi: 10.1016/j.jeem.2019.102255.

[98] C. Herron and J. Wardle, "Technology trajectory and lessons learned from the commercial introduction of electric vehicles in north east England," *Green Energy and Technology*, vol. 203, pp. 161–178, 2015, doi: 10.1007/978-3-319-13194-8_9.

[99] S. Á. Funke, F. Sprei, T. Gnann, and P. Plötz, "How much charging infrastructure do electric vehicles need? A review of the evidence and international comparison," *Transp. Res. Part D: Transp. Environ.*, vol. 77, pp. 224–242, Dec. 2019, doi: 10.1016/J.TRD.2019.10.024.

[100] A. Schroeder and T. Traber, "The economics of fast charging infrastructure for electric vehicles," *Energy Policy*, vol. 43, pp. 136–144, Apr. 2012, doi: 10.1016/j.enpol.2011.12.041.

[101] M. M. Nejad, L. Mashayekhy, R. B. Chinnam, and D. Grosu, "Online scheduling and pricing for electric vehicle charging," *IISE Trans*, vol. 49, no. 2, pp. 178–193, 2017, doi: 10.1080/0740817X.2016.1213467.

[102] S. Bakker, K. Maat, and B. van Wee, "Stakeholders interests, expectations, and strategies regarding the development and implementation of electric vehicles: The case of the Netherlands," *Transp. Res. Part A: Policy Prac.t*, vol. 66, no. 1, pp. 52–64, 2014, doi: 10.1016/j.tra.2014.04.018.

[103] J. Serradilla, J. Wardle, P. Blythe, and J. Gibbon, "An evidence-based approach for investment in rapid-charging infrastructure," *Energy Policy*, vol. 106, pp. 514–524, Jul. 2017, doi: 10.1016/j.enpol.2017.04.007.

[104] C. H. Dharmakeerthi, N. Mithulananthan, and T. K. Saha, "Overview of the impacts of plug-in electric vehicles on the power grid," in *2011 IEEE PES Innovative Smart Grid Technologies, ISGT Asia 2011 Conference: Smarter Grid for Sustainable and Affordable Energy Future*, 2011. doi: 10.1109/ISGT-Asia.2011.6167115.

[105] P. Jochem, E. Szimba, and M. Reuter-Oppermann, "How many fast-charging stations do we need along European highways?" *Transp. Res. Part D: Transp. Environ.*, vol. 73, pp. 120–129, Aug. 2019, doi: 10.1016/j.trd.2019.06.005.

[106] G. Cardoso *et al.*, “Optimal investment and scheduling of distributed energy resources with uncertainty in electric vehicle driving schedules,” *Energy*, vol. 64, pp. 17–30, Jan. 2014, doi: 10.1016/j.energy.2013.10.092.

[107] “AS ‘SADALES TĪKLS’ GADA PĀRSKATS.” Accessed: Jan. 27, 2021. [Online]. Available: https://www.sadalestikls.lv/uploads/2020/04/ST_2019_gada-p-rskats_LV.pdf

[108] “MAJANDUSAASTA ARUANNE.” Accessed: Jan. 27, 2021. [Online]. Available: https://www.elektrilevi.ee/-/doc/8644141/ettevottest/tutvustus/failid/ELV 2019 MAA_tervik.pdf

[109] “Par akciju sabiedrības ‘Sadales tīkls’ elektroenerģijas sadales sistēmas pakalpojuma tarifiem.” Accessed: Jan. 27, 2021. [Online]. Available: https://likumi.lv/ta/id/311033-par-akciju-sabiedribas-sadales-tikls-elektroenergijas-sadales-sistemas-pakalpojuma-tarifiem

[110] L. Held *et al.*, “The Influence of Electric Vehicle Charging on Low Voltage Grids with Characteristics Typical for Germany,” 2019, doi: 10.3390/wevj10040088.

[111] Valsts Ieņēmumu dienests, “Akcīzes nodokļa likmes/Excise tax rates.” Accessed: Jun. 19, 2022. [Online]. Available: https://www.vid.gov.lv/lv/akcizes-nodokla-likmes-0

[112] “Elektroenerģijas nodoklis | Valsts ieņēmumu dienests.” Accessed: Feb. 14, 2024. [Online]. Available: https://www.vid.gov.lv/lv/elektroenergijas-nodoklis

[113] M. S. Kany *et al.*, “Energy efficient decarbonisation strategy for the Danish transport sector by 2045,” *Smart Energy*, vol. 5, p. 100063, Feb. 2022, doi: 10.1016/J.SEGY.2022.100063.

[114] O. Bamisile *et al.*, “A 2030 and 2050 feasible/sustainable decarbonization perusal for China’s Sichuan Province: A deep carbon neutrality analysis and EnergyPLAN,” *Energy Convers. Manag.*, vol. 261, p. 115605, Jun. 2022, doi: 10.1016/J.ENCONMAN.2022.115605.

[115] L. Malka, I. Konomi, P. Bartocci, and E. Rrapaj, 2021, “An Integrated Approach toward a sustainable transport sector using EnergyPLAN model: case of Albania”; Innovations Vol. 9 (2021), Issue 4, pg(s) 141-147**.**

[116] Valdmanis Gunārs, “Modelling of flexibility and integration of renewable energy sources in energy systems,” Master’s thesis, Riga Technical University, Riga, 2019.

[117] “Statistics | Eurostat.” Accessed: Jan. 23, 2023. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/explore/all/transp?lang=en&display=list&sort=category

[118] Oficiālās statistikas portals, “Latvijas energobilance 2021. gadā.” Accessed: Feb. 04, 2023. [Online]. Available: https://stat.gov.lv/lv/statistikas-temas/noz/energetika/publikacijas-un-infografikas/11015-latvijas-energobilance-2021

[119] CSDD, “Rokasgrāmatas par vidējo degvielas patēriņu un CO_2 izplūdi | Vidējais degvielas patēriņš | Transportlīdzeklis.” Accessed: Feb. 18, 2023. [Online]. Available: https://www.csdd.lv/videjais-degvielas-paterins/rokasgramatas-par-videjo-degvielas-paterinu-un-co2-izpludi

[120] International Council on Clean Transportation, “Comparison of fuel consumption and emissions for representative heavy-duty vehicles in Europe.” Accessed: Feb. 18, 2023. [Online]. Available: https://theicct.org/publication/comparison-of-fuel-consumption-and-emissions-for-representative-heavy-duty-vehicles-in-europe/

[121] “Pārvades sistēmas operatora ikgadējais novērtējuma ziņojums”. Accessed: Feb. 04, 2021. [Online]. Available: https://ast.lv/sites/default/files/editor/PSO_zinojums_2019.pdf

[123] "European Biofuels Biofuel Fact Sheet Dimethyl ether (DME) Comparison of Fuel Properties," 2011, Accessed: Mar. 19, 2023. [Online]. Available: www.biofuelstp.eu.

[123] P. Dimitriou and R. Javaid, "A review of ammonia as a compression ignition engine fuel," 2020, doi: 10.1016/j.ijhydene.2019.12.209.

[124] Y. Deng, K.-K. Cao, and Patrick, "Graphical Abstract E-kerosene production in carbon-neutral power systems-a solution for sustainable aviation in Brazil?".

[125] "Statistics | Eurostat." Accessed: Feb. 14, 2024. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/explore/all/transp?lang=en&display=list&sort=category

[126] R. F. Naill, "A system dynamics model for national energy policy planning," *Syst. Dyn. Rev.*, vol. 8, no. 1, pp. 1–19, 1992, doi: 10.1002/sdr.4260080102.

[127] J. D. Sterman, "The Energy Transition and the Economy: A System Dynamics Approach." MIT, Boston, 1981.

[128] T. S. Fiddaman, "Exploring policy options with a behavioral climate-economy model," *Syst. Dyn. Rev.*, vol. 18, no. 2, pp. 243–267, 2002, doi: 10.1002/sdr.241.

[129] Y. Barlas, "Formal aspects of model validity and validation in system dynamics," *Syst Dyn Rev*, vol. 12, no. 3, pp. 183–210, 1996, doi: 10.1002/(sici)1099-1727(199623)12:3<183::aid-sdr103>3.0.co;2-4.

[130] V. Shenbagamuthuraman *et al.*, "State of the art of valorising diverse potential feedstocks for the production of alcohols and ethers: Current changes and perspectives," *Chemosphere*, vol. 286, no. P1, p. 131587, 2022, doi: 10.1016/j.chemosphere.2021.131587.

[131] K. Zeng and D. Zhang, "Recent progress in alkaline water electrolysis for hydrogen production and applications," *Prog. Energy Combust. Sci.*, vol. 36, no. 3, pp. 307–326, 2010, doi: 10.1016/j.pecs.2009.11.002.

[132] "European Energy Exchange," Environmental Markets-Spot Market. Accessed: Dec. 30, 2021. [Online]. Available: https://www.eex.com/en/market-data/environmental-markets/spot-market

[133] "Valsts SIA 'Latvijas Vides, ģeoloģijas un meteoroloģijas centrs,'" Sadaļa Klimats – SEG emisiju un ETS monitorings – Ziņojums par klimatu – Aptuvenās SEG inventarizācijas par X-1 gadu – excel formāta dokuments: "2021. gada inventarizācija par 2020. gadu." [Online]. Available: https://videscentrs.lvgmc.lv/lapas/zinojums-par-klimatu

[134] "Latvijas Centrālās statistikas pārvaldes (CSP) Oficiālās statistikas portāls," Nozare – Enerģētika; Energobilance, TJ, tūkst.toe (NACE 2. red.) 2008–2020. [Online]. Available: https://data.stat.gov.lv/pxweb/lv/OSP_PUB/START__NOZ__EN__ENB/ENB060

[135] "Stella Architect, ISEE SYSTEMS." [Online]. Available: https://www.iseesystems.com/

[136] The European Commission, "Energy Sources, Production Costs and Performance of Technologies for Power Generation, Heating and Transport," SEC (2008) 2872, 2008.

[137] O. Kraan, E. Chappin, G. J. Kramer, and I. Nikolic, "The influence of the energy transition on the significance of key energy metrics," *Renewable and Sustainable Energy Reviews*, vol. 111, pp. 215–223, Sep. 2019, doi: 10.1016/J.RSER.2019.04.032.

[138] D. L. S. Nieskens, D. Ferrari, Y. Liu, and R. Kolonko, "The conversion of carbon dioxide and hydrogen into methanol and higher alcohols," *Catal. Commun.*, vol. 14, no. 1, pp. 111–113, 2011, doi: 10.1016/j.catcom.2011.07.020.

[139] P. Runge, C. Sölch, J. Albert, P. Wasserscheid, G. Zöttl, and V. Grimm, “Economic comparison of different electric fuels for energy scenarios in 2035,” *Appl. Energy*, vol. 233–234, no. September 2018, pp. 1078–1093, 2019, doi: 10.1016/j.apenergy.2018.10.023.

[140] Nityanshi, T. Mathur, V. A. Tikkiwal, and K. Nigam, “Feasibility analysis of a solar-assisted electric vehicle charging station model considering differential pricing,” *Energy Storage*, vol. 3, no. 4, Aug. 2021, doi: 10.1002/EST2.237.

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