RIGA TECHNICAL UNIVERSITY

Kristiāna Dolge

ENERGY SUSTAINABILITY ASSESSMENT METHODS TOWARDS EUROPEAN GREEN DEAL TRANSITION

Summary of the Doctoral Thesis

RTU Press
Riga 2025

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RTU Press
Riga 2025

Dolge, K. Energy Sustainability Assessment Methods Towards European Green Deal Transition. Summary of the Doctoral Thesis. – Riga: RTU Press, 2025. – 51 p.

Published in accordance with the decision of the Promotion Council “RTU P-19” of 13 December 2024, Minutes No. 214.

This Thesis research has been supported by the Latvian Council of Science, project “Climate Neutrality Decision Models in Action”, No. VPP-KEM-Klimatneitralitāte-2023/1-0002. This Thesis has also been supported by the European Social Fund within the Project No. 8.2.2.0/20/I/008, “Strengthening of PhD students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialization”.

Cover picture from www.shutterstock.com

https://doi.org/10.7250/9789934371639

ISBN 978-9934-37-163-9 (pdf)

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 April 16, 2025, at 14:00, 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.

Kristiāna Dolge ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, 3 chapters, Conclusions, 41 figures, and 36 tables; the total number of pages is 296, including appendices. The Bibliography contains 166 titles.

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INTRODUCTION

The global economy is on the verge of one of the greatest transitions in modern history. The ability to strengthen national securities and ensure sustainable economic development and prosperity while significantly reducing consumption of energy resources and generated greenhouse gas (GHG) emissions is a global challenge that affects every country in the world. The focus on strengthening security, boosting stagnating economies, and addressing the urgent need for climate change mitigation dominates the global political agenda. The current geopolitical situation has highlighted that energy – its availability, sustainability, and strategic use – is at the core of all these challenges.

In the European Union (EU), the energy sector accounts for more than 75 % of the EU's greenhouse gas emissions [1], plays a crucial role in driving economic growth, is a primary factor behind the rising cost of living [2], and serves as a cornerstone for enhancing security. The future of energy transition nowadays is determined by rapidly changing policy decisions rather than purely by market forces as experienced in the past. Once primarily a technological and occasionally geopolitical matter, energy has shifted to become one of the most critical aspects of economic policy and a source of conflict among competing interest groups [3].

Expanding political frameworks, such as the European Green Deal and REPowerEU – which set strategic energy and climate objectives – have pushed national policymakers to assess the current state of energy sustainability and shifted the energy sector toward the adoption of new solutions for how energy is produced, supplied, consumed, and accumulated [4]. Over the years, the energy system has transformed from a highly centralized, fossil fuel-based system to a more decentralized and energy-efficient system, with a growing integration of variable renewable energy sources (RES). This shift highlights the importance of increasing system flexibility. The adoption of energy storage solutions and the transition to smart energy systems have become key guiding principles for developing a sustainable energy infrastructure for the future.

This Thesis explores the progress made in Latvia's energy transition and the challenges faced in moving towards a future smart energy system. It examines the current landscape of energy sector development in Latvia within the broader context of the European Union. It provides an in-depth analysis of the current state of energy sustainability in Latvia and assesses its progress toward the green energy transition, thereby offering a comprehensive overview and uncovering various aspects of energy sustainability.

Research topicality

By 2050, the EU has pledged to become a climate-neutral continent [5]. In order to achieve these ambitious goals, a set of strategic policies for the coming decades has been established and announced. One of the key targets set by the European Green Deal is to reduce GHG emissions by at least 55 % by 2030 compared to the emission levels observed in 1990 [6]. The energy sector is the largest source of GHG emissions not only globally but also in Latvia. In 2022, the energy sector, along with transport, accounted for 63.3 % of Latvia's total GHG emissions (Fig. 1). Therefore, achieving these ambitious climate targets will require proactive implementation of measures focused on decarbonization and enhancing energy efficiency in the energy sector [7].

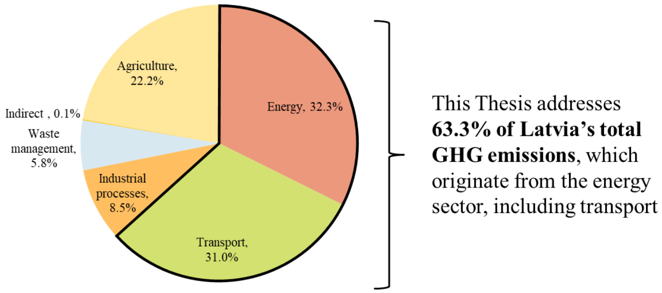

Fig. 1. Distribution of GHG emissions in Latvia by sectors in 2022, excluding LULUCF [8].

The current climate policy framework requires urgent changes and upgrades to the existing energy infrastructure. However, the complexity of the energy policy, which is constantly balancing between the climate neutrality targets, economic prosperity and national security, highlights the need for deeper insights to support more informed decision-making. There is a need for better assessment tools to guide national decision-makers in developing effective strategies and adopting best practices for a sustainable energy transition.

Aim and objectives

The aim of this Thesis is to develop an integrated energy sustainability assessment model that identifies the key drivers and challenges of the energy transition on Latvia's path to climate neutrality within the context of the European Green Deal and REPowerEU policies.

To achieve the research aim, six interrelated objectives are set:

1. Develop methods to assess the current level of energy sustainability and the progress made in energy system decarbonization across three distinct scales of energy systems: sectoral (including industry and transport), municipal, and national.
2. Use a benchmarking approach to compare energy sustainability trends in Latvia with those of the Baltic States and the EU.
3. Conduct a macroeconomic assessment to identify key drivers and foundational elements in energy policy that promote a more sustainable, independent, and green energy infrastructure.
4. Assess the role of energy storage in the energy transition and compare various energy storage technologies.
5. Analyze social factors influencing the transition to smart energy systems, such as the increased deployment of energy storage technologies in local energy transitions.
6. Develop a method for policy risk evaluation to help avoid policy pitfalls in the future.

Hypothesis

An integrated energy sustainability assessment model can be applied to evaluate the level and trend of energy transition in industry, transport and the overall energy sector and identify best practice solutions that could be applied to achieve the long-term targets of the European Green Deal policy.

Novelty

The novelty of this Thesis derives from three key aspects of the applied research framework: the multifunctionality and coverage of the developed method, the multidisciplinary approach, and its broad geographical application.

Firstly, this Thesis develops a novel energy sustainability assessment model that combines several unique methods that have not been combined and used for the in-depth analysis of Latvian energy systems before, as illustrated in Fig. 2. Decomposition analysis was used to discover historical developments in energy systems and progress towards sustainability. Decomposition analysis is combined with composite index methodology, which allows the examination of multiple aspects of energy sustainability and benchmarks to identify best practice examples. PESTLE analysis was used to investigate available energy storage technology alternatives, which are crucial for increasing energy system flexibility and sustainability. Moreover, the fuzzy cognitive mapping method was used to examine the social factors that influence the transition to smart energy systems that integrate energy storage solutions. To obtain a macroeconomic view of climate neutrality and the driving forces of GHG emissions, the Kaya identity equation was used to compare Latvia's progress in emission reduction with the Baltics and EU member states. To gain insights into what should be accounted for when designing smart energy policies and avoiding potential pitfalls in the future, a novel policy risk due to diligence framework is introduced.

The advantage of combining these methods is that it allows for a comprehensive examination of the current state and the progress made toward achieving energy sustainability from multiple perspectives, such as technical, environmental, economic, social, and political. Moreover, the developed method of this Thesis offers an insightful examination of the energy policy of energy systems at four different levels – sectoral (including industry and transport), local (with a focus on municipal energy system scale), national, and international.

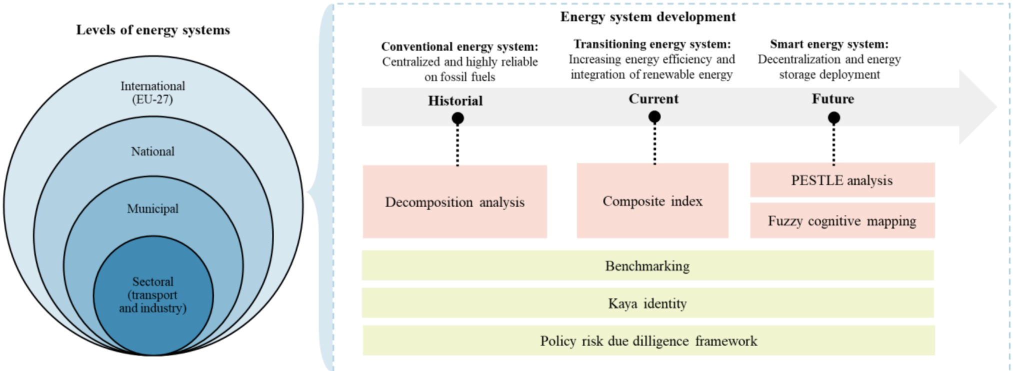

Fig. 2. Research framework and scientific novelty of the Thesis.

Secondly, this study uses a multidisciplinary approach by considering multiple dimensions of energy sustainability and by incorporating a macroeconomic perspective in energy systems analysis. In this way the model helps to identify key cornerstones and opportunities within the broader context of energy policy.

Thirdly, the analyses in this Thesis encompass the entire European Union by comparing the development of the Latvian energy system with that of the EU-27 countries. This innovative benchmarking approach enables the identification of both the frontrunners and the laggards in EU energy sustainability, offering valuable insights into the relative performance of each country.

Practical relevance

This Thesis has high practical applicability as it offers valuable data-driven insights that can greatly improve decision-making in energy policy, climate strategy, and the development of roadmaps across various levels of energy systems. It introduces sustainability assessment techniques that integrate benchmarking methods and combine a wide range of assessment indicators. These techniques are designed for direct use by policymakers, energy sector shapers and stakeholders such as electricity grid operators, district heating companies, manufacturing companies, and transport infrastructure developers. They provide a practical way to measure and monitor energy sustainability in a thorough and comprehensive manner. The benchmarking approach also serves as a useful toolkit, helping to identify best practices based on factual data. Policymakers at local, national, and EU levels can use the developed methods to make better-informed decisions, shape effective energy policies and address gray areas in current energy and climate planning.

Approbation of the research results

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12. Dolge, K., Blumberga, D. What are the Linkages between Climate and Economy? Bibliometric Analysis. Environmental and Climate Technologies, Vol. 26, No. 1, 2022, pp. 616–629, doi:10.2478/rtuect-2022-0047

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Vol. 25, No. 1, pp. 331–342. ISSN 1691-5208. e-ISSN 2255-8837, doi:10.2478/rtuect-2021-0024

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Approbation of the research results at scientific conferences

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4. Dolge, K., & Blumberga, D. What are the Linkages between Climate and Economy? Bibliometric Analysis, *International Scientific Conference of Environmental and Climate Technologies CONECT 2022*, Riga, Latvia, May 11–13, 2022.
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6. Dolge, K., Toma, A. S., Grāvelsiņš, A., Blumberga, D. Multidimensional Factors Influencing Renewable Energy Storage Deployment: PESLTE Analysis. *International*

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Structure of the Thesis

This Doctoral Thesis is based on five main thematically unified segments based on full approbation through publications in internationally recognized scientific journals and participation in international scientific conferences. Table 1 outlines the scientific articles used in this Thesis, grouped by the main segments. The overall Thesis structure is displayed as a journey of the energy sector's development through time with respect to decreasing its emissions and, at the same time, maximizing sustainability, which is analyzed through a combination of different methods, as illustrated in Fig. 3.

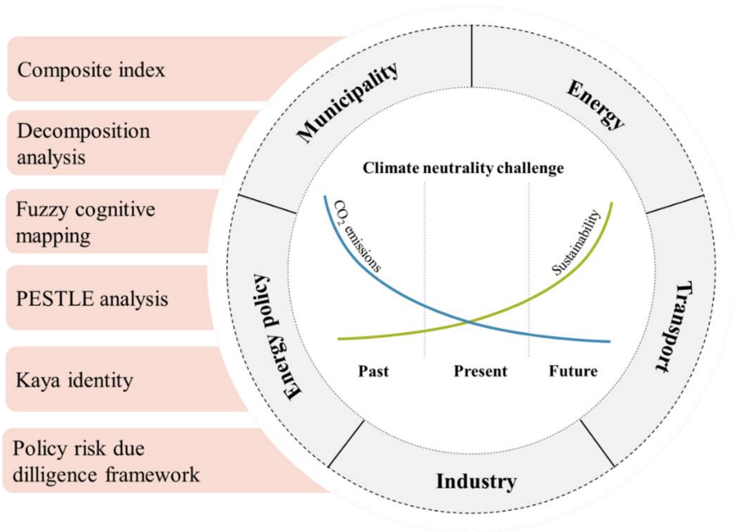

Fig. 3. Structure of the Thesis results.

This Thesis is composed of an Introduction and four main sections: (1) a literature review; (2) research methodologies; (3) results and discussion; and (4) a conclusion. The Introduction section presents the key characteristics of research topicality, the Thesis novelty and practical significance. It presents the Thesis aim and hypothesis, as well as outlines the approbation of the published research results.

Table 1

Scientific Articles Used in the Doctoral Thesis

Segment	No	Publication title
Industrial sector	1	Composite Index for Energy Efficiency Evaluation of Industrial Sector: Sub-Sectoral Comparison.
	2	Key Factors Influencing the Achievement of Climate Neutrality Targets in the Manufacturing Industry: LMDI Decomposition Analysis.
Transport sector	3	The Status Quo of the EU Transport Sector: Cross-Country Indicator-Based Comparison and Policy Evaluation.
Energy sector	4	From Targets to Action: Analyzing the Viability of REPowerEU in Achieving Energy Sustainability.
	5	Transitioning to Clean Energy: A Comprehensive Analysis of Renewable Electricity Generation in the EU-27.
	6	How Independent is the Energy Sector in the EU?
Municipal energy systems	7	Realizing Renewable Energy Storage Potential in Municipalities: Identifying the Factors that Matter.
	8	Energy Transition Reality Check: Are Municipalities Meeting the Mark?
	9	What Drives Energy Storage Deployment in Local Energy Transitions? Stakeholders' perspective.
Climate and energy policy	10	Economic Growth in Contrast to GHG Emission Reduction Measures in Green Deal Context.
	11	Composite Risk Index for Designing Smart Climate and Energy Policies.
	12	What are the Linkages between Climate and Economy? Bibliometric Analysis.

Chapter 1 of the Thesis presents a literature review of the existing climate and energy policy governing the long-term development of the energy sector and key guiding principles. Chapter 2 includes a description of the applied research methodologies, outlining the key approaches in developing composite indices, decomposition analysis frameworks, and the fuzzy cognitive mapping approach. Chapter 3 includes the results and discussion sections, which are structured into the five aforementioned segments.

The description of the results begins with the analysis of a less polluting sector – industry – and proceeds to an in-depth examination of the most polluting sectors, transport and energy. The results of the energy sector are described in two main parts – the national energy system and the outlook on national GHG emission drivers in the overall economy – followed by a municipal energy system result analysis. It then explores insights into the deployment of smart energy systems, particularly from the perspective of energy storage integration. Finally, developed policy risk due diligence framework results are presented along with the challenges of designing climate and energy policies. The final chapter of this Thesis presents the conclusions of this research.

1. LITERATURE REVIEW

Energy transition policy

The European Green Deal strategy has set the goal of the European Union becoming the first climate-neutral continent by 2050 by combining ambitious climate action with economic growth and prosperity enhancement [9]. Since the energy sector accounts for the vast majority of the EU's greenhouse gas emissions [1], achieving these ambitious climate targets will necessitate the proactive implementation of measures focused on decarbonization and enhancing energy efficiency in the energy sector [7]. To this end, the European Parliament has declared that the EU's Renewable Energy Directive will be enhanced, and it is planned to increase the binding renewable energy target from 32 % to at least 42.5–45 % by 2030 nearly doubling a share of RES in EU energy consumption compared to 2022 [10]. In the future, as smart energy systems continue to evolve, there will be a substantial increase in the electrification of end-use consumption, since it is expected that the electricity demand in the EU will increase by at least 32 % by 2050 compared to its current levels [11]. This shift will be driven by the growing adoption of electrical appliances like heat pumps and cooling systems, as well as efforts to decarbonize transportation [12]. Furthermore, the REPower EU initiative, which aims to achieve full independence in the EU from Russian energy resources such as natural gas, oil and coal, underlines the urgent need for EU Member States to rapidly expand their current renewable energy generation capacities in the coming years [13].

The switch to these variable sources requires a larger degree of flexibility and introduces more complexities into energy system infrastructures. Part of this complexity lies in the intermittent nature of renewable energy. The production of renewable energy, although possessing integral value, does not consistently correspond with peak demand periods, hence displaying pressure on power systems due to fluctuations. The unpredictability of solar and wind power might result in the occurrence of energy surpluses or shortages. The efficient storage of additional power during times of low demand and subsequent release when required is crucial. The usage of energy storage has seen a significant global deployment owing to its key function in grid management. The system offers the advantage of backup power and more flexibility, as well as helps to reduce emissions.

The energy transition in the EU is forcing the entire infrastructure of the energy system to change and adapt. National energy systems are experiencing a shift from large, centralized fossil fuel power plants to decentralized, smaller renewable energy generation plants [14]. Decentralization has brought the energy sector under local government management, pushing for more active involvement in energy planning and sector decarbonization to reach national and global climate neutrality targets [15]. As a result of the decentralized nature of smart energy systems, municipalities have emerged as the main cornerstone for regional climate neutrality. Municipal utilities are taking on more responsibility and participating in the development of the regional energy infrastructure [15]. Municipalities are both consumers and energy planners, providers and advisors for their energy end-user groups [15], [16]. Municipalities own and operate regional energy facilities due to the dispersed nature of renewable energy generation and the decentralized structure of the energy sector.

Background information on energy in the EU and Latvia

Energy sector, including transport, was the main source of GHG emissions in both the EU-27 and Latvia, contributing 77 % and 63 % of total GHG emissions in 2022, respectively (Fig. 1.1). Transport, household and industrial sectors constituted to the majority of the total energy end-consumption in both EU-27 and Latvia, with transport (31 %) constituting the highest share in EU-27 and households (29 %) in Latvia. Industry is the third largest energy consumer in both EU-27 and Latvia [17].

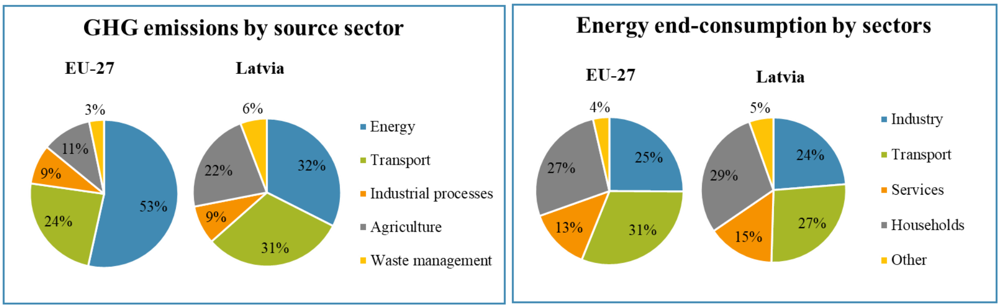

Fig. 1.1. GHG emissions and energy consumption by sectors in the EU and Latvia in 2022 [18], [17].

In the EU-27, RES accounted for 38 % of total electricity production in 2022, with wind energy (15 %) and hydro energy (10 %) holding the largest shares (Fig. 1.2). Solar PV followed with 7 %, while biomass and other renewables, including biogas, geothermal, tidal, and wave energy, altogether contributed 3 %, and nuclear energy contributed 22 %. Fossil fuels, along with natural gas and other accounted for 20 % of total electricity production [18]. In 2022, Latvia's electricity production was less diversified, with hydro energy dominating at 55 %. Biomass contributed 11 %, wind and solar PV 5 %, and other renewables 5 %. Natural gas accounted for 24 %, bringing the total renewable share to 76 % [17].

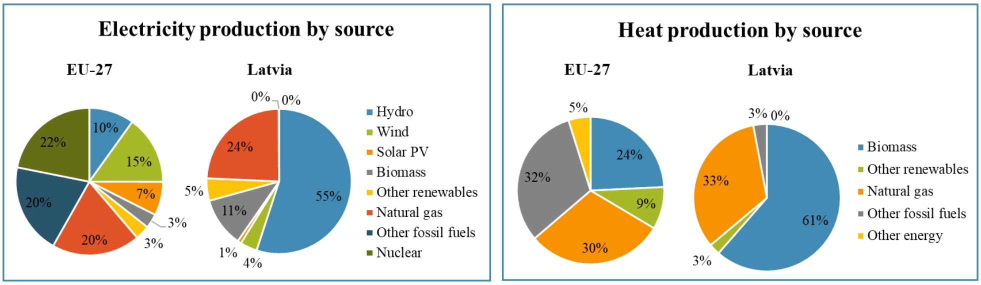

Fig. 1.2. Gross electricity and heat production by source in the EU and Latvia in 2022 [17].

The heat sector remains less decarbonized compared to electricity production. In the EU-27, fossil fuels accounted for 62 % of total gross heat production in 2022, with natural gas comprising 30 % and other fossil fuels making up 32 %. Biomass played a significant role, contributing 24 %, while other renewables, including geothermal and solar thermal, accounted for 9 %. In Latvia, biomass dominated gross heat production in 2022, representing 61 % of the total. Wood pellets, wood chips, and other wood products were extensively utilized for heat generation. Natural gas was the second-largest contributor, accounting for one-third of Latvia's total gross heat production [17].

2. METHODOLOGY

2.1. Composite index

The overall calculation procedure for the construction of the composite sustainability index consisted of six main chronological steps: (1) selection and grouping of the indicators; (2) indicator impact evaluation; (3) data normalization according to Eqs. (2.1) and (2.2); (4) indicator weight assessment; (5) indicator aggregation according to Eqs. (2.3) and (2.4), and (6) benchmarking using index average values.

$$I_N^{+} = \frac{I_{act} - I_{min}}{I_{max} - I_{min}}, \quad (2.1)$$

$$I_N^{-} = 1 - \frac{I_{act} - I_{min}}{I_{max} - I_{min}}, \quad (2.2)$$

$$I_D = \sum w \times I_N^{+} + \sum w \times I_N^{-}, \quad (2.3)$$

$$CI = \sum w \times I_D, \quad (2.4)$$

where

I_N^{+} and I_N^{-} – normalized indicators of a positive and negative impact, respectively;

I_{act} – the actual value of an indicator;

I_{max} and I_{min} – the maximum and minimum value of an indicator, respectively;

I_D – the sub-index of a particular dimension;

w – the value of the determined weight of an indicator;

CI – the final composite index.

This study used the composite index methodology to develop indices in multiple sub-models. Table 2.1 summarizes the composite indices developed and the characteristics of the methods applied.

Table 2.1

Summary of Composite Indices Developed

Level	Composite index	Year	Comparison	Dimensions	Indicators	Method	Weighting
Industry	Industrial composite energy efficiency index	2017	Cross-sectoral	3	12	Quanti-tative	Equal
Transport	Transport composite sustainability index	2017	Cross-country	4	15	Quanti-tative	Equal
National energy	Energy sustainability index	2019	Cross-country	n/a	6	Quanti-tative	Equal
Municipal energy	Municipal energy transition index	2022	Cross-municipal	4	9	Mixed	Equal
Energy storage	PESTLE composite index	2023	Cross-technology	6	19	Mixed	Expert
Policy	Policy risk index	2021	Cross-case	6	24	Mixed	Equal

Industrial energy efficiency index

The industrial energy efficiency index (EEI) was constructed to investigate energy sustainability performance across 18 main industrial sub-sectors of Latvia in 2017. The developed composite index consisted of 12 different explanatory indicators grouped in three main dimensions of energy efficiency – economic, technical, and environmental, as illustrated in Fig. 2.1.

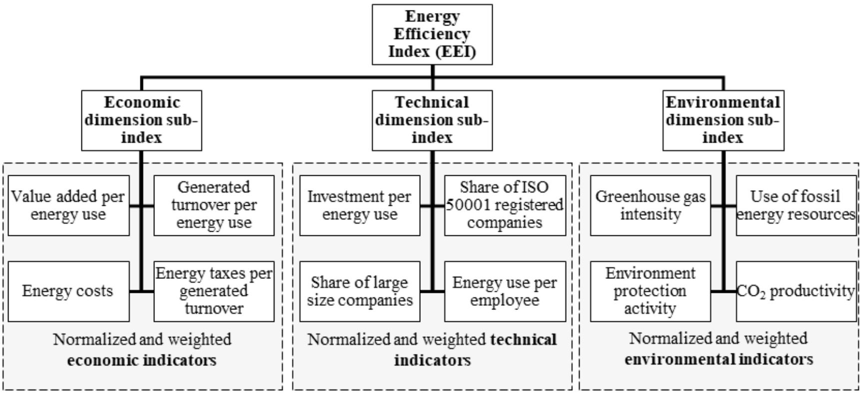

Fig. 2.1. Industrial energy efficiency index indicators and classification.

Transport sustainability index

The transport sustainability index was constructed to assess the overall sustainability level of the transport sector in all European Union Member States (except Malta) and the United Kingdom using the composite sustainability index method for cross-country comparison. Countries were compared using 15 transport indicators grouped into four dimensions (mobility, sustainability, innovation, and environment) based on the latest available data from 2017, as outlined in Fig. 2.2.

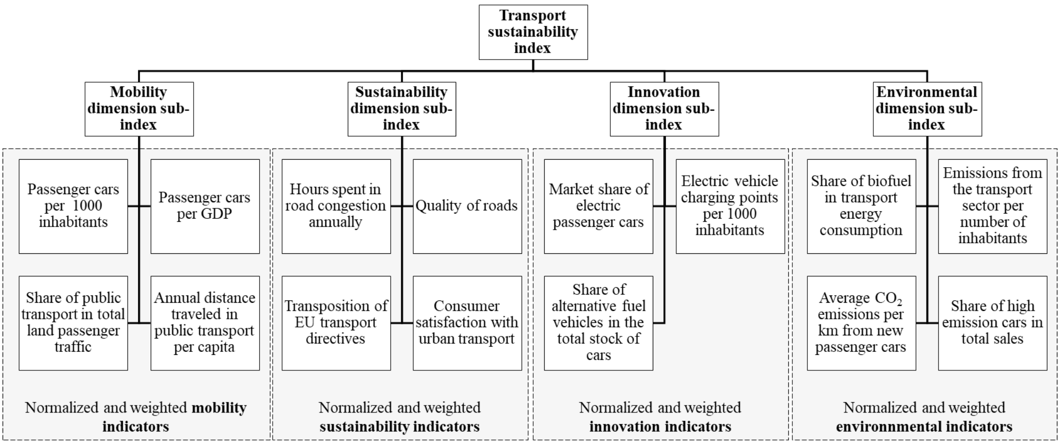

Fig. 2.2. Transport sustainability index indicators and classification.

National energy sustainability index

The energy sustainability composite index (ESCI) was constructed to compare different profiles of energy sustainability in the 27 EU member states. The developed composite index integrated six indicators characterizing energy sustainability components – energy import dependency, share of renewable energy sources, primary energy intensity, energy efficiency, CO_2 emission intensity, and energy poverty. Fig. 2.3 outlines the selected indicators of the energy sustainability composite index. Data was selected for 2019.

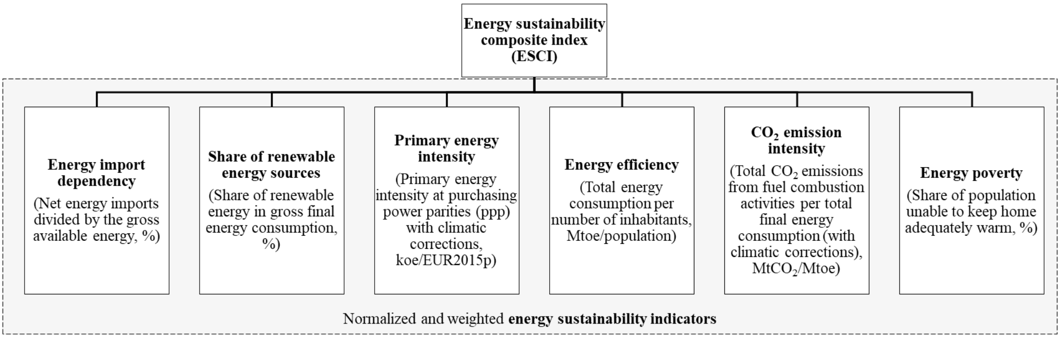

Fig. 2.3. Energy sustainability composite index (ESCI) indicators.

Municipal energy transition index

The municipal energy transition index was constructed, incorporating nine indicators grouped into three main dimensions of sustainable municipal energy transition: energy efficiency, energy decarbonization, and smart energy system deployment, as outlined in Fig. 2.4. Five municipalities of the Baltic Sea Region were analyzed, and their energy transitions were assessed: the Gulbene municipality (Latvia), Tukums municipality (Latvia), Taurage municipality (Lithuania), Tomelilla municipality (Sweden), and Wejherowo municipality (Poland).

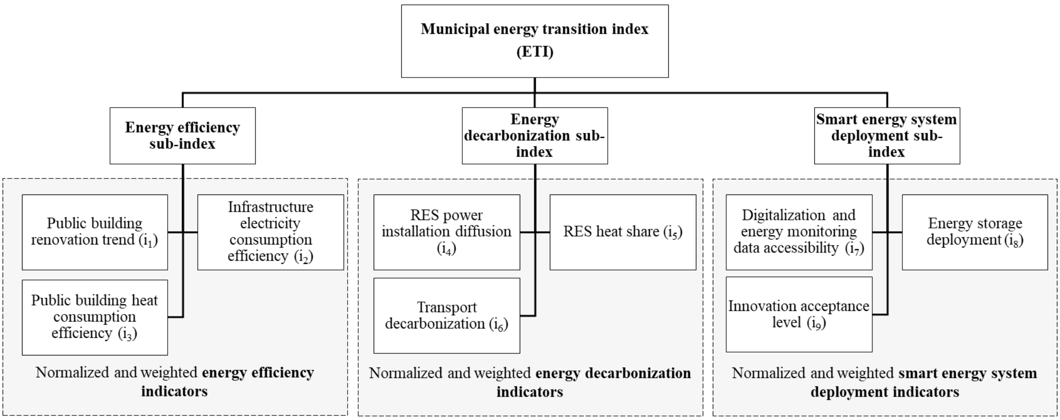

Fig. 2.4. Municipal energy transition index indicators and classification.

Energy storage PESTLE composite index

The PESTLE framework was applied to select and analyze relevant factors that influence the deployment of different RES storage technologies in a municipal context. To compare technologies based on the PESTLE analysis indicators, the composite index method was applied to quantify and measure the influencing factors for each technology. PESTLE composite index indicators are illustrated in Fig. 2.5.

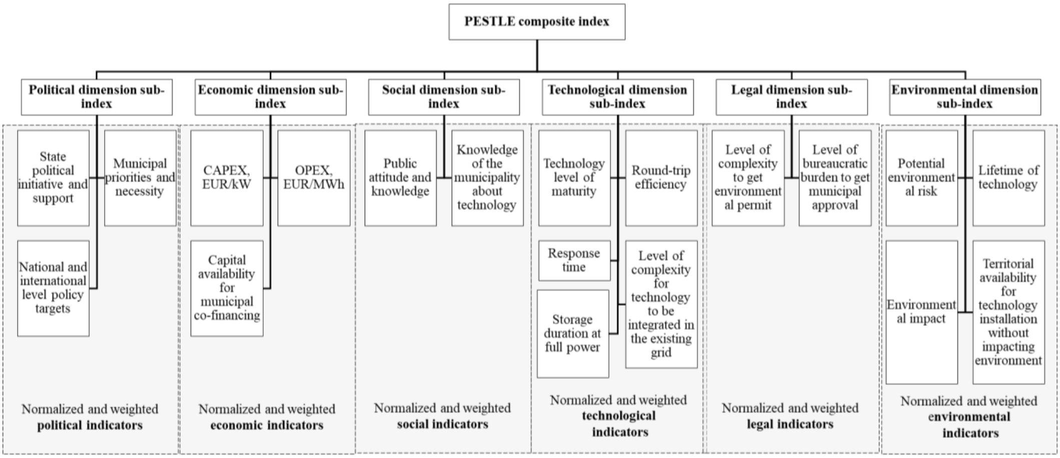

Fig. 2.5. Energy storage PESTLE composite index indicators and classification.

The developed model was approbated in a case study in Gulbene municipality where four different alternative energy storage technologies were compared: (1) lithium-ion batteries; (2) water-based sensible thermal storage (hot water tanks); (3) power-to-gas (hydrogen); (4) power-to-liquid (biomethane). Expert weights were used to calculate the PESTLE composite index. The values of the weights were obtained from the surveys with municipality representatives – for political dimension 0.32, for economic 0.27, for social 0.13, for technological 0.10, for legal 0.08, and for environmental 0.09.

Policy risk index

A risk matrix framework combined with a composite index methodology was applied to produce a policy risk index composed of 24 risk indicators grouped into six main risk categories, as illustrated in Fig. 2.6. Risk matrix framework combines two main components (1) probability or likelihood of risk occurring and (2) severity of consequences that will arise as a result of risk occurrence [19]. Risk score is calculated as the multiplication between the grades of risk likelihood and risk consequence, as demonstrated in Eq. (2.5). Obtained risk scores were normalized, weighted and aggregated.

$$R_i = R_{\text{likelihood}} \times R_{\text{consequence}}, \quad (2.5)$$

where R_i – a risk score;
$R_{\text{likelihood}}$ – the obtained score of a risk likelihood;
$R_{\text{consequence}}$ – the obtained score of a risk consequence.

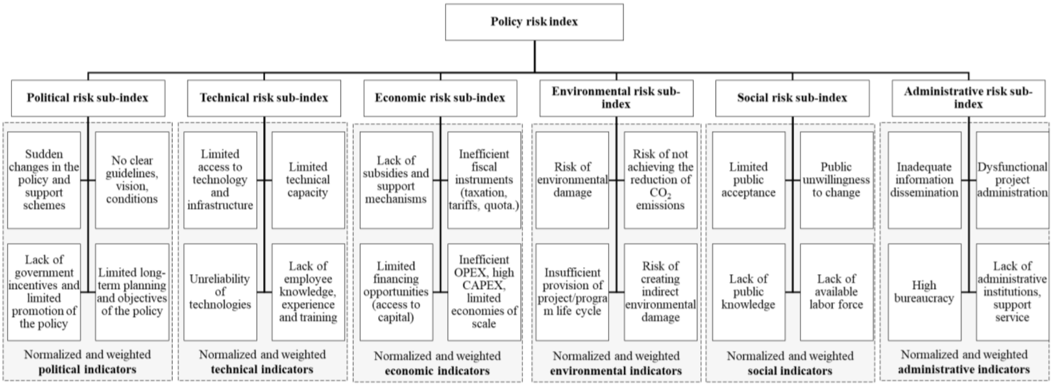

Fig. 2.6. Policy risk index indicators and classification.

The model was applied to assess five climate policy instruments – construction of wind energy park (Case 1), energy efficiency monitoring system program (Case 2), the climate financial instrument (Case 3), development of distributed energy generation (Case 4), development of centralized energy generation (Case 5). Each case study was evaluated by a group of five energy experts.

2.2. Decomposition analysis

The logarithmic mean Divisia index (LMDI) decomposition analysis additive approach was used to examine the main drivers of change in CO_2 and GHG emissions in different sectors (industry, transport, energy and overall economy), power production from renewable energy resources, and net energy imports over a given time span. Table 2.2 summarizes the LMDI analyses developed.

Table 2.2

Summary of LMDI Decomposition Analyses Developed

Level	Measuring (*Y*)	Decomposers (X_n)	Years	Comparison (*i*)
Industry	Industrial energy-related CO_2 emissions	Activity, structural, energy intensity, fuel mix, emission intensity	1995–2019	Cross-sectoral
Transport	GHG emissions from fuel combustion in transport	Emission intensity, RES transition, energy intensity, economic growth, population growth	2010–2019	Cross-country
National energy	CO_2 emissions from fuel combustion	Emission intensity, energy intensity, GDP growth, population growth	2015–2019	Cross-country
National RES	Gross electricity production from renewables	RES share, energy intensity, RES capacity productivity, RES deployment per capita, population growth	2012–2021	Cross-country Cross-technology
Energy independence	Net energy imports	Energy dependency, energy efficiency, economic growth, population growth	1995–2020	Cross-country
Overall economy: Kaya identity	Total GHG emissions	Emission intensity, energy intensity, GDP growth, population growth	2010–2019 Forecasting 2030	Cross-country

The change in the indicator being studied (*Y*) over the defined period of time is expressed as a subject of numerous explanatory drivers (X_n), as expressed in Eq. (2.6), retrieved from [20].

$$Y = X_1 \times X_2 \times X_3 \times \dots \times X_n \,, \tag{2.6}$$

where Y denotes the indicator being measured, and X_n denotes the number of decomposers or explanatory drivers of changes in indicator *Y*.

Since change in aggregate level of *Y* changes from initial year 0 to year *T*, then *Y* in a base year $Y^0 = \sum_i X_1{}^0 X_2{}^0 X_3{}^0 X_n{}^0$ and $Y^T = \sum_i X_1{}^0 X_2{}^0 X_3{}^0 X_n{}^0$. The change in *Y* between year 0 and year *T* is determined using LMDI I additive decomposition analysis technique, according to Eq. (2.7).

$$\Delta Y = Y^T - Y^0 = \Delta\, Y_{X1} + \Delta\, Y_{X2} + \Delta\, Y_{X3} + \Delta\, Y_{Xn} \,, \tag{2.7}$$

where $\Delta\, Y_{Xn}$ denotes the effect on *Y* from changes in driver X_n.

Each effect is further expressed using Eq. (2.8).

$$\Delta\, Y_{Xn} = \sum_i \frac{Y^T - Y^0}{\ln Y - \ln Y^0} \ln \frac{X_{n1}^{\ T}}{X_{n1}^{\ 0}} \,, \tag{2.8}$$

where

Y^T – the value of an indicator in future year *T*;

Y^0 – the of an indicator in initial year;

i – the value of the subject under study (e.g. country, sector, technology).

Industrial sector

Total energy-related CO_2 emissions in industry were determined as a sum of energy-related CO_2 emissions of each industrial sub-sector (according to the NACE Rev. 2 nomenclature). CO_2 emissions in industry were decomposed according to Eq. (2.9).

$$C = \sum_{ij} C_{ij} = \sum_{ij} Q \frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} = \sum_i Q S_i I_i F_{ij} M_{ij} \,, \tag{2.9}$$

where

C – total aggregated energy-related CO_2 emissions;

Q – total produced volumes expressed as total value-added;

E – total energy consumption;

S_i – industrial production activity;

I_i – energy intensity;

F_{ij} – fuel mix;

M_{ij} – the emission factor.

A subscript *i* denotes the representative value of a subsector; its absence represents the total value of the industry. A subscript *j* denotes the type of energy product in the total energy balance. The further decomposition calculation was performed based on Eqs. (2.7) and (2.8).

Transport sector

LMDI decomposition analysis was applied to measure changes in aggregate GHG emissions of the transport sector determined by emission intensity effect, RES transition effect, energy intensity effect, economic growth effect, and population growth effect. GHG emissions from fuel combustion in transport in 28 EU countries were decomposed using Eq. (2.10) based on [21], [22].

$$GHG = \sum_i GHG_i = \sum_i \frac{GHG}{FFC} \cdot \frac{FFC}{TEC} \cdot \frac{TEC}{GDP} \cdot \frac{GDP}{POP} \cdot POP = \sum_i EM_i \cdot RES_i \cdot EN_i \cdot GDP_i \cdot POP_i \,, \tag{2.10}$$

where

GHG – GHG emissions from fuel combustion in transport;
FFC – fossil fuel consumption in the transport sector;
TEC – total energy consumption in the transport sector;
GDP – gross domestic product;
POP – the number of inhabitants;
i – specific country.

Furthermore, each indicator was expressed as a factor contributing to changes in GHG emissions, and further decomposition construction and calculation was performed based on Eqs. (2.7) and (2.8). Time series data from 2010 to 2019 were used for all the selected LMDI decomposition analysis indicators.

National energy sector

The LMDI decomposition analysis method was used to analyze how the overall CO_2 emissions from fuel combustion have changed from 2015 to 2019 for all EU-27 countries. Changes in total energy CO_2 emissions were explained by determining four main factors-emission intensity, energy intensity, economic growth, and population growth-according to Eq. (2.11), as retrieved from [23]. The further decomposition construction and calculation were performed based on Eqs. (2.7) and (2.8).

$$CO_2 = \sum_i CO_{2_i} = \sum_i \frac{CO_2}{En} \frac{En}{GDP} \frac{GDP}{Pop} POP, \tag{2.11}$$

where

CO_2 – CO_2 emissions in a given period;
En – energy consumption in period;
GDP – gross domestic product in the period;
POP – the population in the period;
i – the country.

Renewable electricity generation

The LMDI decomposition analysis was used to decompose the changes in production values of gross electricity from renewable energy sources over the 10-year period from 2012 to 2021. Five main decomposition factors were determined to construct the LMDI for changes in electricity generation from RES over the years as outlined in Eq. (2.12), adapted from [24] and [25]. Moreover, this study extends the LMDI decomposition analysis to examine how wind and solar PV installations contribute to the overall increase in renewable energy sources, according to Eqs. (2.13) and (2.14).

$$RES = \sum_i RES_i = \sum_i \frac{RES}{EN}\frac{EN}{GDP}\frac{GDP}{RCAP}\frac{RCAP}{POP}POP = \sum_i RSH_i\, EI_i RPR_i RD_i POP_i\ , \tag{2.12}$$

$$W = \sum_i W_i = \sum_i \frac{W}{RES}\frac{RES}{EN}\frac{EN}{GDP}\frac{GDP}{WCAP}\frac{WCAP}{POP}POP = \sum_i WSH_i RSH_i\, EI_i WPR_i WD_i POP_i\ , \tag{2.13}$$

$$PV = \sum_i PV_i = \sum_i \frac{PV}{RES}\frac{RES}{EN}\frac{EN}{GDP}\frac{GDP}{PVCAP}\frac{PVCAP}{POP}POP = \sum_i PVSH_i RSH_i\, EI_i PVPR_i PVD_i POP_i\ , \tag{2.14}$$

where
RES – gross electricity production from renewables;
W – gross electricity production from wind;
PV – gross electricity production from solar PV;
EN – total gross electricity production;
GDP – gross domestic product;
POP – total population;
EI – energy intensity effect;
RCAP, WCAP, PVCAP – electricity production capacities from RES, wind, and solar PV, respectively;
RSH, WSH, PVSH – RES, wind and solar PV share effect, respectively;
RPR, WPR, PVPR – RES, wind, and solar PV capacity productivity effect, respectively;
RD, WD, PVD – RES, wind and solar PV deployment per capita effect, respectively.

Variations in RES-produced electricity are further determined by variations in each LMDI decomposer, and the further decomposition calculation was performed based on Eqs. (2.7) and (2.8).

Energy independence

The LMDI decomposition analysis method was used to study changes in net energy imports of EU countries. Changes in net energy imports were determined by four main factors – changes in energy dependency, changes in energy efficiency, changes in economic growth, and changes in population, as indicated in Eq. (2.15). Net energy imports are expressed as energy imports minus energy exports.

$$NI = \sum_i NI_i = \sum_i \frac{NI}{EN}\frac{EN}{GDP}\frac{GDP}{POP}POP = \sum_i DEP_i\, EE_i EC_i POP_i, \tag{2.15}$$

where
NI – net energy imports;
EN – gross available energy;
GDP – gross domestic product;
POP – population;
DEP is energy import dependency,
EE – energy efficiency;
EC – economic growth;
i – a particular country.

Further decomposition calculation was performed based on Eqs. (2.7) and (2.8). All the data was collected from the Eurostat database for all 27 EU member states for the period from 1995 to 2020.

Kaya identity

The LMDI decomposition method combined with the Kaya identity was used to explain changes in overall GHG emissions in the economy by determining four main factors-emission intensity, energy intensity, economic growth, and population growth according to Eq. (2.16), as retrieved from [23]. The analysis is conducted for a 10-year period from 2010 to 2019 for the EU-28 countries (including the UK).

$$GHG = \sum_i GHG_i = \sum_i \frac{GHG}{En}\frac{En}{GDP}\frac{GDP}{Pop}Pop = \sum_i EMI_i\, ENI_i GDP_i POP_i\,, \tag{2.16}$$

where

GHG – greenhouse gas emissions in a certain period;
En – energy consumption in period;
GDP – gross domestic product in the period;
POP – the population in the period;
EMI – emission intensity;
ENI – energy intensity.

Further decomposition construction and calculation were performed based on the Eqs. (2.7) and (2.8). If we assume that α, β, δ, ε are growth rates of the representative factors, namely, emission intensity, energy intensity, economic growth, and population change, then future values for each factor can be forecasted using Eq. (2.17). The same relationship holds true for other factors.

$$EMI^T = EMI^0 \cdot (1 + \alpha) \tag{2.17}$$

Following the fundamental basis of Kaya identity as demonstrated in Eq. (2.16) and coping it with Eq. (2.17), forecasted GHG emissions were obtained using Eq. (2.18).

$$GHG^T = GHG^0 \cdot (1+\alpha)\cdot(1+\beta)\cdot(1+\delta)\cdot(1+\varepsilon) \tag{2.18}$$

Further yields are obtained as explained in a relationship that is demonstrated in Eqs. (2.19) and (2.20).

$$\Delta\, EMI = z \cdot (1+\alpha) \tag{2.19}$$

$$z = \frac{GHG^0 \cdot [(1+\alpha)\cdot(1+\beta)\cdot(1+\delta)\cdot(1+\varepsilon) - 1]}{ln[(1+\alpha)\cdot(1+\beta)\cdot(1+\delta)\cdot(1+\varepsilon) - 1]} \tag{2.20}$$

The same relationship holds true for other factors. To derive Eq. (2.21), Eqs. (2.19) and (2.20) are further inserted into Eq. (2.16).

$$GHG^T = GHG^0 + z\cdot(1+\alpha) + z\cdot(1+\beta) + z\cdot(1+\delta) + z\cdot(1+\varepsilon) \tag{2.21}$$

Future GHG emission values can be projected using Eq. (2.21) or Eq. (2.24) if growth rates are defined for each factor (EMI, ENI, GDP, POP). They are determined using an exponential smoothing forecast based on values from 2010 to 2019. The forecast is carried out for a period from 2020 to 2030 with three main forecast scenarios: (1) existing measures (base values); (2) additional measures (lower 95 % confidence bound values); and (3) business as usual (upper 95 % confidence bound values).

2.3. Fuzzy cognitive mapping

Fuzzy cognitive mapping (FCM) methodology was used to analyze the mental models of different stakeholders regarding their perceived importance of different factors influencing the implementation of energy storage in municipalities. The multi-level stakeholder cognitive mapping approach used in this study followed several research steps, as illustrated in Fig. 2.7.

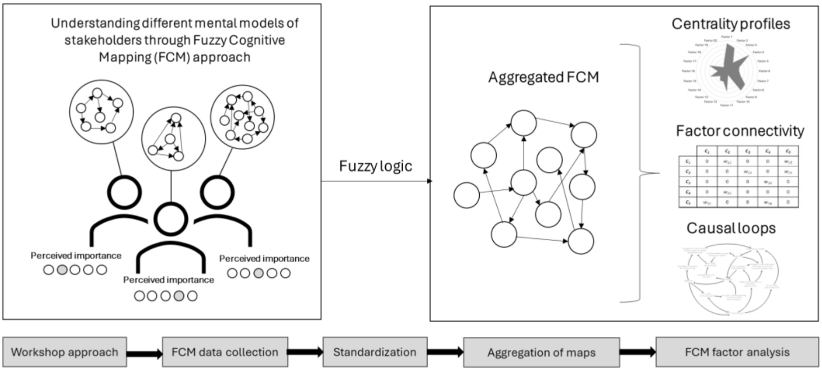

Fig. 2.7. Multi-level stakeholder cognitive mapping methodological approach.

First, a methodological approach for FCM data collection was developed and implemented to obtain mental model data from the key stakeholders of the local energy transition. Two workshops were organized to collect FCM data and analyze the different perceptions of stakeholders. The stakeholders involved in the mental model workshops were from five main groups of expertise: research organizations, municipality representatives, energy clusters and consultancies, local infrastructure providers, and sectoral agencies. The individual mental models were then compiled, standardized and aggregated. Map condensation and aggregation were used to better explain the structure of individual cognitive maps.

To measure the strength of the impact of the factors outlined in the mental models, the centrality score was analyzed. Generally, a higher centrality index value indicates the importance of a factor to other related factors. A high level of centrality indicates the factor through which the flow must pass for the system to function properly. Centrality was calculated by combining the indegree and outdegree values of the adjacency matrix.

3. RESULTS

3.1. Industrial sector

3.1.1. Industrial energy efficiency index

The energy efficiency index (EEI) was constructed to evaluate and depict energy efficiency performance across the 18 main manufacturing sectors in Latvia. Overall, all sectors indicate weak energy efficiency with an industry average EEI score of 0.39. The environmental dimension sub-index, with an average score of 0.48, has the most significant contribution to the overall EEI. Both economic and technical dimension sub-indices, on average, scored on approximately the same level, reaching the numbers of 0.34 and 0.35, respectively. Fig. 3.1 illustrates EEI results and dimension sub-index results.

The five sectors with the highest EEI values were computer, electronic and optical products manufacturing (0.70), electrical equipment manufacturing (0.52), pharmaceutical products manufacturing (0.52), printing and reproduction of recorded media (0.50), and machinery and equipment manufacturing (0.48) sectors. Five leading sectors reached dominating values in each of the dimension sub-indices, which consequently led to a higher overall EEI value. Despite the leading positions of these sectors, it is essential to notice that none of the leading sectors demonstrated a strong position in all dimensions and their respective indicator values. This means that while a sector might achieve the highest value in one dimension, it lacks certain factors to dominate at the same level in another dimension.

On the contrary, the five sectors with the lowest EEI numbers were non-metallic mineral products (0.04), wood and products of wood and cork (0.23), mining and quarrying (0.24), basic metals (0.32), and chemicals and chemical products manufacturing (0.33).

Average EEI values ranging from 0.34 to 0.48 were obtained for the rest of the sectors. The manufacture of computer, electronic and optical products achieved the highest EEI score, mainly because of the high values it reached in the economic and environment sub-dimension. It is explained by the sector's ability to produce high value-added products with relatively low energy inputs. The sector is knowledge-intensive since it has a strong science base and is highly reliant on human capital and intellectual property; thus, the economic value that the sector generates surpasses the energy inputs that are required in the product manufacturing process. The results indicate that manufacturing more complex and knowledge-intensive or lightweight products results in higher energy efficiency [26].

On the other hand, the manufacturing of basic commodities and raw materials such as non-metallic mineral products, wood, mining and metal products are associated with lower energy efficiency since these industries indicated the lowest EEI values. The underperformance of these sectors is partly explained by the sector specifics that require high energy and resource inputs such as large facilities, high-capacity machinery and competitive labor productivity, therefore making these sectors highly energy intensive and sensitive. The generated economic value of the products produced in these sectors is insufficient to compensate for the energy that was consumed in the production process of the products. It emphasizes the potential opportunities for energy efficiency improvement in these sectors. From this, it can be concluded that EEI is highly dependable on the sector's energy productivity, which is measured by the generated value added and turnover per unit of consumed energy. Therefore, the higher the economic value the produced product can generate, the more representable the overall EEI is achieved. It is affordable to produce more secondary products with high added value and competitive advantage even though they consume some amount of energy; however, it is not affordable to waste energy on primary products of low added value consuming large amounts of energy. As a result, energy efficiency should be increased primarily in energy-intensive sectors.

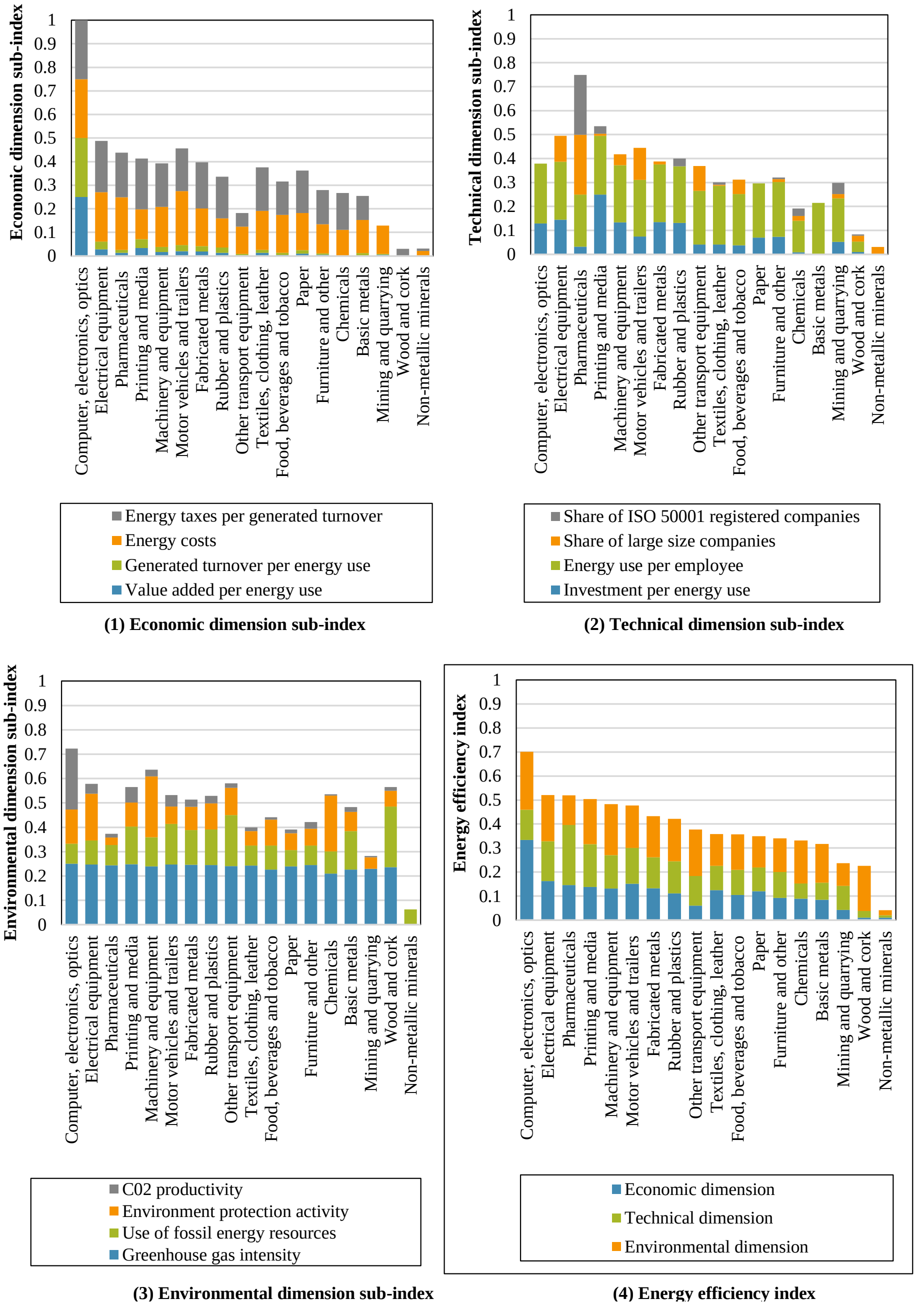

Fig. 3.1. Economic, technical, and environmental dimension sub-indices and the overall energy efficiency index for the 18 selected Latvian manufacturing industry sectors in the year of 2017.

3.1.2. Industrial LMDI decomposition analysis

Decomposition analysis has been constructed for the Latvian manufacturing industry to monitor changes in total industrial CO_2 emissions over the period from 1995 to 2019 determined by five main factors: industrial activity effect – structure effect, energy intensity effect, fuel mix effect, and emission intensity effect. The study period was divided into five groups, each accounting for a 5-year time interval. Fig. 3.2 shows the LMDI results in combination with the CO_2 growth rates during the period.

The overall CO_2 growth rate in the Latvian manufacturing industry has been fluctuating over the study period. Steady decreases were observed for the periods from 1995 to 2000 and from 2010 to 2015, when the CO_2 growth rates were –22 % and –26 %, respectively. However, in the intervals from 2000 to 2005 (+1 %) and from 2005 to 2010 (+3 %), the CO_2 growth rate indicated an upward trend, while in the interval from 2015 to 2019, the CO_2 growth rate was equal to –1 %. CO_2 reduction in the manufacturing industry has stagnated in recent years, and there has been little improvement in the last 5 years.

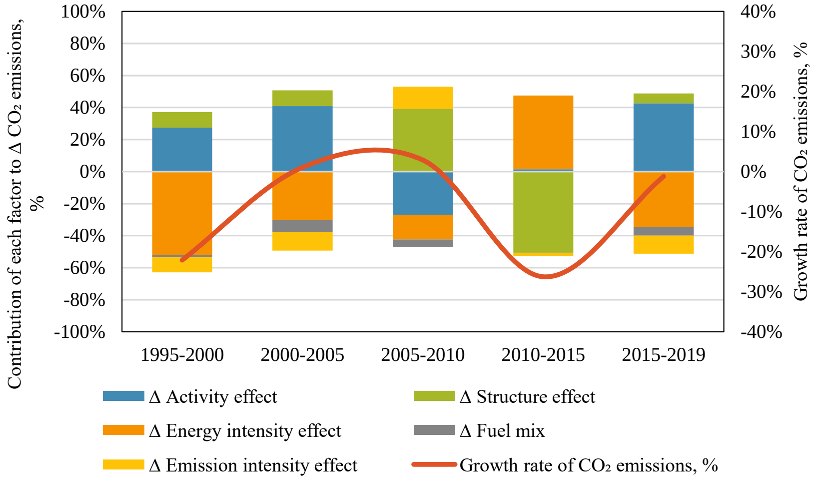

Fig. 3.2. Aggregated decomposition analysis results for the time periods.

Over the period of ten years, the manufacturing industry experienced a shift from one energy-intensive sector (metal manufacturing) to another no less energy-intensive sector (wood processing). However, the competitive advantage of the wood products manufacturing sector is the high share of RES utilization where wood residues and chips are used in thermal processes that is a CO_2-neutral fuel. If the aggregate values of the period are analyzed, excluding 2013, which distorted the entire industry, the energy intensity effect played the most important role in reducing CO_2 emissions.

The overall decomposition results show a positive trend towards the implementation of decarbonization measures, which in aggregate contributed to a reduction in overall emissions intensity in the industry. However, energy efficiency measures had a more than six times larger overall effect on CO_2 reduction compared to RES measures. The main reason for the increase in industrial CO_2 emissions is the effect of industrial activity, explained by the gradual annual increase in the volume of industrial production, which subsequently also led to an increase in total energy consumption to compensate for the increase in [27]. In total, from 2015 to 2019, a larger decrease in energy intensity in industry was observed compared with the first half of the decade. Part of the explanation in energy efficiency activity in the past five years can be explained by autonomous developments in the companies where in order to increase company competitiveness there is a constant need to look for ways to decrease energy costs. However, another part of the explanation lies in the effect of policies that might have stimulated larger energy savings and achievement of more ambitious energy efficiency targets. Fig. 3.3 illustrates the contribution of each effect on changes in CO_2 emissions and the overall change in generated CO_2 emissions in each sub-sector in the time period from 2015 to 2019.

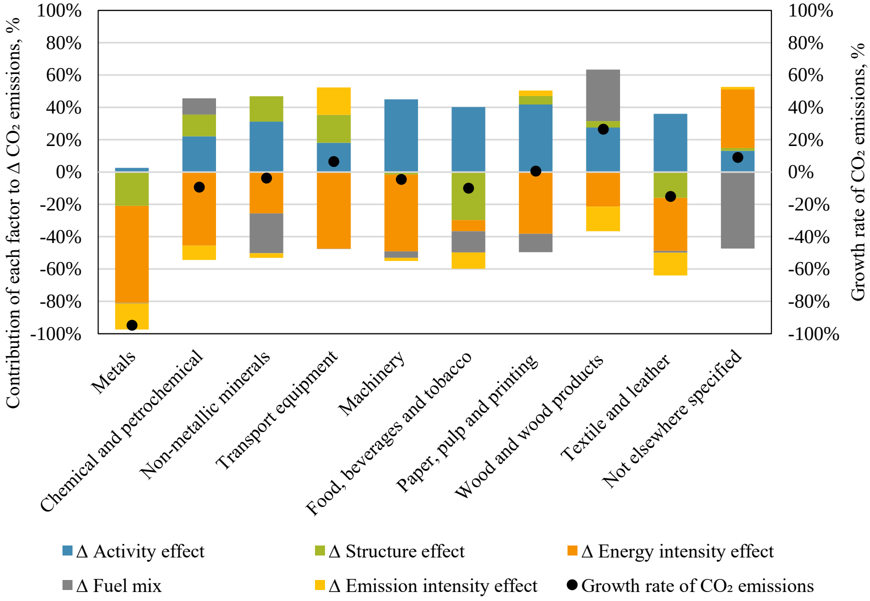

Fig. 3.3. CO_2 emission decomposition for the time period from 2015 to 2019.

In total, in 2019, almost all manufacturing industry sub-sectors indicated a reduction in CO_2 emissions compared to the levels of 2015. However, three sectors reported the opposite. In 2019, CO_2 emissions increased by 6 % in the transport equipment production sector, by 26 % in the wood processing sector and by 9 % in other sub-sectors compared to 2015. The wood processing sector and chemical and petrochemical production sector were the only sectors that indicated a negative tendency towards increasing the share of RES. Both sectors showed the opposite trend in their fuel mixes, indicating a decrease of RES in the total energy mix. The results show that despite significant energy efficiency improvements in these sub-sectors, the total rise in industrial activity, structural effect, and fuel mix effect counteracted the energy intensity effect. Therefore, current energy efficiency improvements could not compensate for these effects, which drove up the overall CO_2 emissions at a much higher pace than implemented energy efficiency measures.

Industrial activity was the main reason for the sharp increase in the total energy consumption of the wood processing sector during the period studied. The increasing demand for wood chips, wood pellets and other wood products in the largest global export markets made the wood processing sector the fastest growing sector of Latvian industry and led to a significant annual increase in production volume over the last decade [27]. Latvia's wood processing sector has seen exports increase by 82 % in the last decade (over the period 2010–2019) [28], and 60 % of the total wood products produced in Latvia were exported in 2019. Thus, the development of the sector is strongly influenced by the demand on international export markets [29].

According to the decomposition analysis results, the fuel mix effect in the wood processing sector has been the main driver of the increase in CO_2 emissions over the last five years. It shows that the sector has reduced its overall share of RES in the total fuel mix, signalling a negative trend. An increase in fossil energy consumption in the wood sector was observed during the periods from 2014 to 2018. In part, this could be explained by the fact that the overall demand for wood products, particularly wood pallets and chips, has increased across the global trade market, which has also pushed factories to increase their capacity. As a result, deficiencies in wood residues and wood chips, which are mostly used for combustion processes, have been compensated by natural gas or fossil energy. This also increased the total CO_2 emissions generated in the industry.

The results suggest that sectoral heterogeneity should be taken into account to design more efficient energy and emission saving policies, as there exist different incentives between high and low carbon intensity sectors. For high carbon intensive sectors such as non-metallic mineral manufacturing, emissions trading schemes or fiscal instruments such as carbon taxes are effective mechanisms to achieve energy and carbon savings. For sectors with low emission intensity, such as the wood processing industry, financial incentives, subsidies and obligation schemes, e.g. mandatory energy audits, could be used as effective mechanisms to promote energy efficiency and decarbonization activities. Sector-specific benchmarks and standards could potentially be created and defined in the industrial energy policy.

Greater upscaling of clean energy technologies will be needed in the future to accelerate the pace of decarbonization, and additional policy measures should, therefore, be taken. Policies should support both investment in capital for companies deploying clean technologies and investment in research and development to ensure the development of innovative technologies for sustainable energy systems. Mechanisms such as financial subsidies, tax exemptions and additional access to capital could be used as effective tools for long-term industrial development and sustainability policies. Given the high energy intensity of the manufacturing sector in Latvia, which is mainly dominated by two sectors – wood processing and non-metallic mineral production – investments in heat recovery technologies could be one of the main drivers of energy and carbon emission savings in the industry. Moreover, fiscal instruments such as energy taxes and carbon pricing could be used as effective tools to promote clean energy sources and to restructure the overall energy mix of sub-sectors that depend on high fossil fuel consumption. The phasing out of carbon-intensive energy sources could be achieved by making their price less attractive and renewable energy sources more affordable for businesses.

3.2. Transport sector

3.2.1. Composite transport sustainability index

The transport composite sustainability index incorporated 15 indicators grouped into four dimensions: mobility, sustainability, innovation, and environment. The results showed two main benchmarks – the average value and the lowest value. The average value represents the average sub-index value of all countries in the respective dimension and was calculated as the arithmetic mean of all values. The lowest value represents the lowest sub-index value among the analyzed countries, which was determined by a minimum value function in the data set. Fig. 3.4 illustrates mobility dimension sub-index values. Mobility dimension indicators describe the socio-economic aspects of transport system sustainability. The highest scores for the mobility dimension sub-index were obtained by Hungary, which scored high on all indicators included in the dimension. The results showed that the share of public transport in total land passenger traffic was the most important factor in ranking countries in the highest (Hungary and the Czech Republic) and lowest (Lithuania and Poland) positions in the mobility dimension.

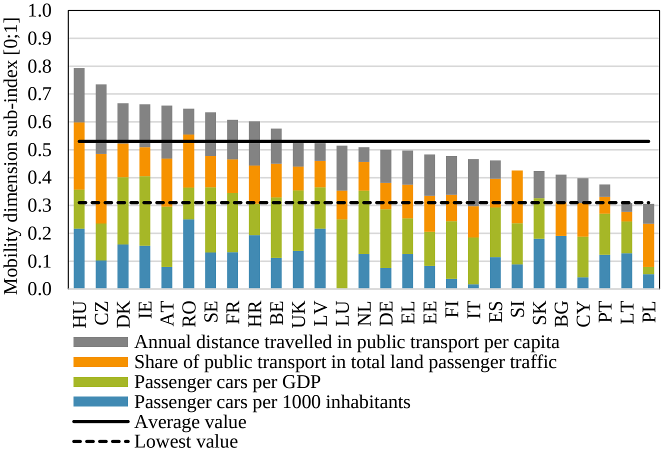

Fig. 3.4. Mobility dimension sub-index.

Fig. 3.5 shows the sub-indices of the sustainability dimension. For most countries, the indicator scores for consumer satisfaction with urban transport and the implementation of EU transport directives were the most critical, negatively affecting the overall score of the sustainability dimension. This suggests that countries should emphasize improving consumer attitudes towards public transport use, which will help shift society's habits towards more sustainable travel measures. Governments should be more proactive in adapting to the framework of the EU transport directives, which aim to increase the energy efficiency, safety, and sustainability of all transport infrastructure in all Member States.

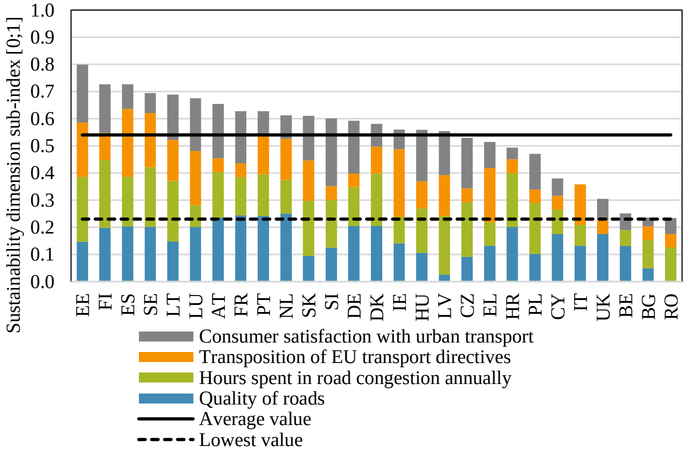

Fig. 3.5. Sustainability dimension sub-index.

Fig. 3.6 demonstrates the sub-index values of the innovation dimension. As can be observed, the values of the innovation sub-index for all countries were, on average, significantly lower than the values of the other dimension sub-indices. Leading countries like Sweden and the Netherlands were showing a greater pace of innovation in the transport sector and transformation to more environmentally friendly measures such as using alternative fuel vehicles and electric cars. In contrast, most other countries were just starting to build the necessary infrastructure for non-fossil fuel transport and lagged behind the leaders.

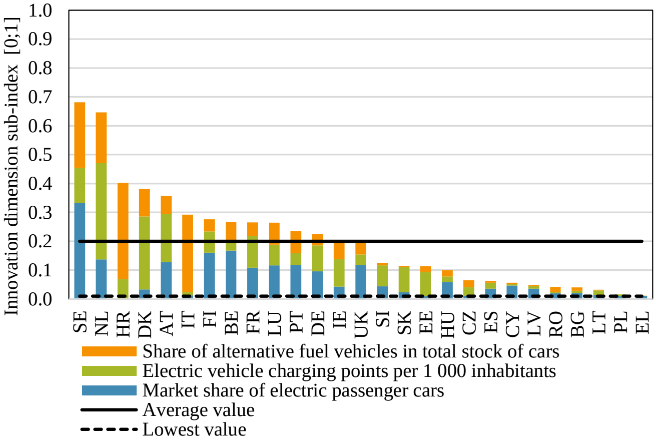

Fig. 3.6. Innovation dimension sub-index.

Fig. 3.7 illustrates the sub-indices of the environmental dimension for all countries included in the study. All countries except Sweden had the lowest values for the indicator of biofuels' share in transport energy consumption. In most countries, there is still untapped potential for replacing fossil fuels and increasing the volume of biofuel use. In several countries, such as Cyprus, Hungary, Finland, Slovakia, Latvia, and Estonia, the share of high-emission cars in total sales was still significant. This showed a negative trend in consumer behavior, which lowered the overall score for the sub-indices of the environmental dimension and the long-term sustainability of the transport sector.

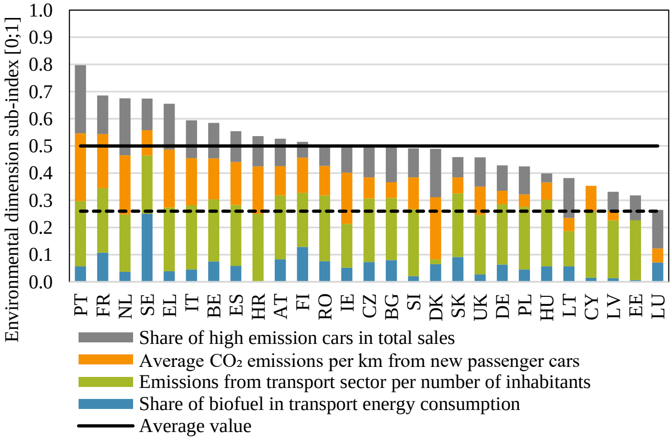

Fig. 3.7. Environmental dimension sub-index.

The composite transport sustainability index results were classified into four groups of sustainability levels, as shown in Fig. 3.8. The leading countries in transport sustainability were Sweden, the Netherlands, Austria, France, and Denmark. In all these countries, equal attention has been paid to all dimensional indicators, which has helped to achieve a higher level of sustainability. In general, a high level of untapped sustainability potential was found for all the countries studied, which was reflected in the overall score of the composite sustainability index. None of the countries achieved the highest possible score of 1. Even in the leading countries, many positions require more significant efforts to transform the transport system towards climate-neutral and sustainable measures.

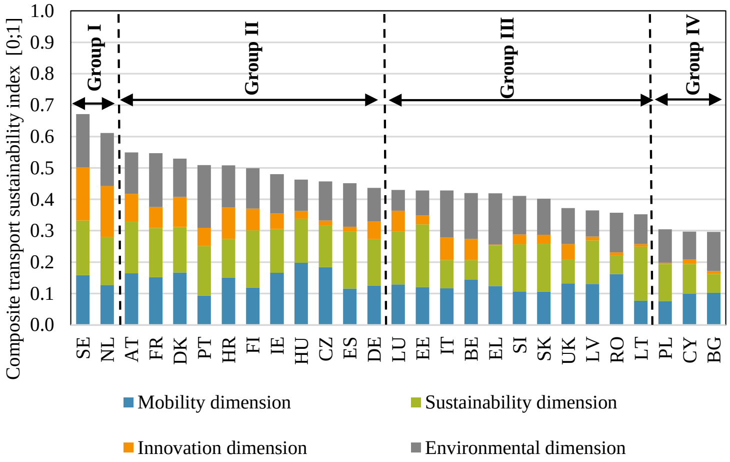

Fig. 3.8. Composite transport sustainability index.

3.2.2. Transport LMDI decomposition analysis

The LMDI decomposition analysis method analyzed changes in GHG emissions from the transport sector based on five primary factors: emission intensity, RES transition, energy intensity, economic growth, and population growth. Fig. 3.9 illustrates the LMDI decomposition analysis results of GHG emissions of the transport sector from 2010 to 2019 (thousand tons of CO_2 equivalent) for each country. In general, 12 of 28 countries have reduced GHG emissions from the transport sector over the ten years from 2010 to 2019, with Greece (–20.7 %), Sweden (–20.2 %), Finland (–11.4 %), and the Netherlands (–10.8 %) achieving the most considerable emission reductions. The majority of countries increased their GHG emissions from transport fuel combustion, with the highest increases in Lithuania (43.4 %), Poland (34.0 %), Malta (34.7 %), Romania (33 %), and Bulgaria (24.1 %).

In Latvia, total GHG emissions from transport fuel combustion increased by 1.6 % from 2010 to 2019. Since 2012, annual transportation-related GHG emissions have increased in Latvia primarily due to rising economic growth, but GHG emission declines have been observed since 2017. The impact of the transition to RES in the Latvian transport sector began to predominate only in 2017. Since 2012, the Latvian transport sector has shown considerably small decreases in energy intensity, which means that no significant improvements in energy efficiency were observed in the Latvian transport sector, and the use of transport modes with high specific fuel consumption factors predominated. The increase in emission intensity in 2017 indicated an increasing shift from public transport to the higher use of private vehicles, which put additional pressure on Latvian initiatives to reduce GHG emissions in the transport sector. In the composite transport sustainability index, Latvia ranked 22nd with a score of 0.36, significantly below the EU average value. Latvia had low use of public transport, poor road quality, less developed infrastructure for alternative fuel vehicles (low share of electric cars and biofuel consumption), and a high share of high-polluting vehicles in the total stock of vehicles compared to other countries that prevened for the achievement of higher GHG emission cuts in the transport sector.

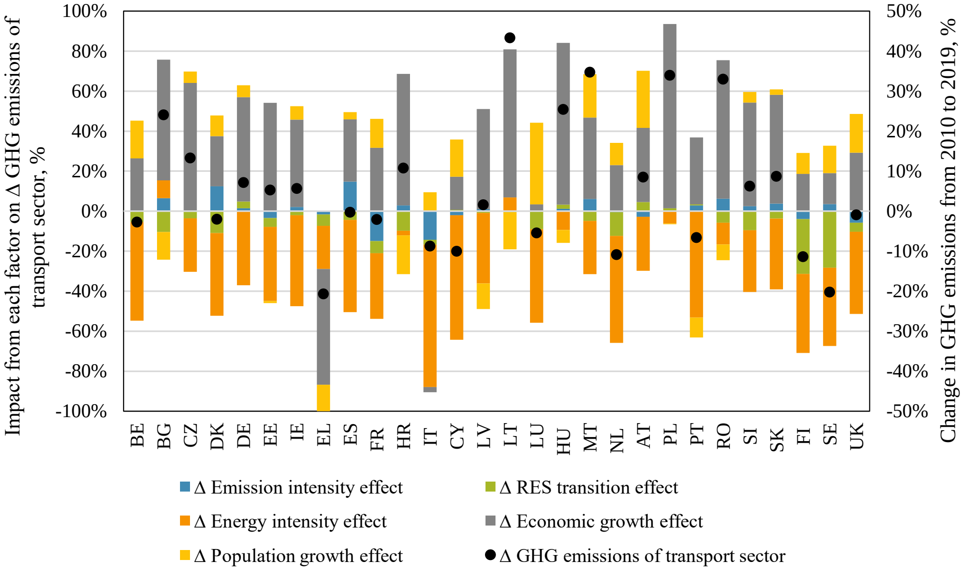

Fig. 3.9. LMDI decomposition analysis results of GHG emissions of transport sector from 2010 to 2019 (thousand tons of CO_2 equivalent) for each country.

The study highlights that innovation is the key factor distinguishing Nordic countries, which lead in electric and alternative fuel vehicle adoption, from Eastern and Western Europe. Eastern European countries lag significantly, with CO_2 intensities and fuel consumption nearly three times higher than in Nordic countries, largely due to an older vehicle fleet dominated by second-hand imports, reflecting lower income levels. In less developed countries with weak transport sustainability performance levels, transport policies focus on promoting existing measures (e.g., the use of low-blend biofuels) and shifting responsibility for transport climate neutrality targets to specific groups (e.g., fuel suppliers), most of whose funding is based on EU structural funds. In the Eastern European countries and in part of the Western European countries, the priority is to increase institutional support and recognition of the critical performance of the transport sector in relation to climate change mitigation measures. Proactive infrastructure planning and the development of more ambitious future development strategies should be introduced. Renewal of the existing vehicle fleet is critical in Eastern European countries to increase energy efficiency in the transport sector. Therefore, stricter regulations should be applied to limit the use of old and carbon-intensive vehicles. In addition, both Nordic and Eastern European countries should establish mechanisms that would facilitate the transition from private cars to public transportation. Behavioral changes are crucial for the future sustainable transport policy, where public transport is the key element of decarbonization.

3.3. Energy sector

3.3.1. Analysis of the national energy sector using composite index and LMDI

The energy sustainability composite index (ESCI) was developed to explore and compare the multiple lawyers of energy sustainability, including energy security, primary energy intensity, share of renewable energy resources, energy efficiency, CO_2 emission intensity, and energy poverty. Fig. 3.10 depicts the ESCI results. ESCI results are categorized into three primary groups: Group I consists of countries that have achieved ESCI results above the average, Group II is comprised of countries whose average ESCI score is equivalent to the EU average, and Group III is comprised of countries that significantly lag behind in energy sustainability and have ESCI results below the average of 0.54.

With a score of 0.79, Sweden achieved the highest result among all countries. This is due to the high values obtained for all indicators except primary energy intensity, which indicates that Sweden has a slightly higher primary energy intensity than other EU member states. Denmark attained the second highest ESCI score, 0.74, and displayed consistently favorable results across all indicators. The Group I category encompasses countries such as Latvia (0.69), Romania (0.66), Croatia (0.63), Austria (0.63), France (0.60), Estonia (0.59), and Finland (0.59). Nevertheless, this cluster of countries exhibits distinct patterns of strengths and weaknesses in their energy sustainability. Estonia's energy self-sufficiency is among the highest in the European Union, as evidenced by its energy import dependency score. However, the country's renewable energy resource share is notably lower, and its primary energy intensity is higher, both of which have a detrimental impact on its energy sustainability.

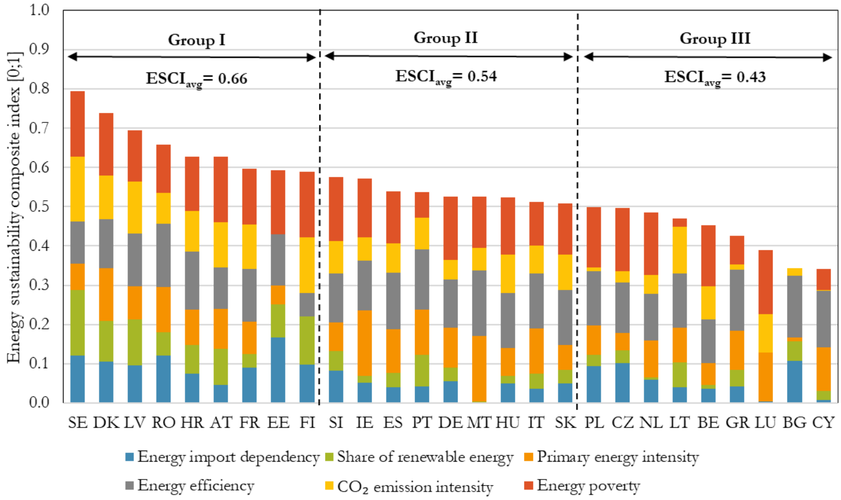

Fig. 3.10. Energy sustainability composite index (ESCI) results for EU-27 countries.

Group II countries overall show significantly higher energy import dependency compared to Group I countries, which negatively affected their overall ESCI score. Significantly lower results were also reported for the share of renewable energy sources compared to leading countries in Group I. Group III countries had the weakest indicators of energy poverty, share of renewable energy resources, and CO_2 emission intensity, which negatively impacted their ESCI score overall. The countries with the lowest total ESCI scores were Bulgaria and Cyprus, which both received 0.34. Overall, it can be observed that there is potential for enhancing the energy sustainability of all countries, as none of them attained the maximum score of 1. Further analysis used LMDI decomposition analysis to track the progress of energy policy in achieving reductions in energy-related CO_2 emissions from 2015 to 2019. Fig. 3.11 shows the results of the LMDI decomposition analysis for all EU-27 countries.

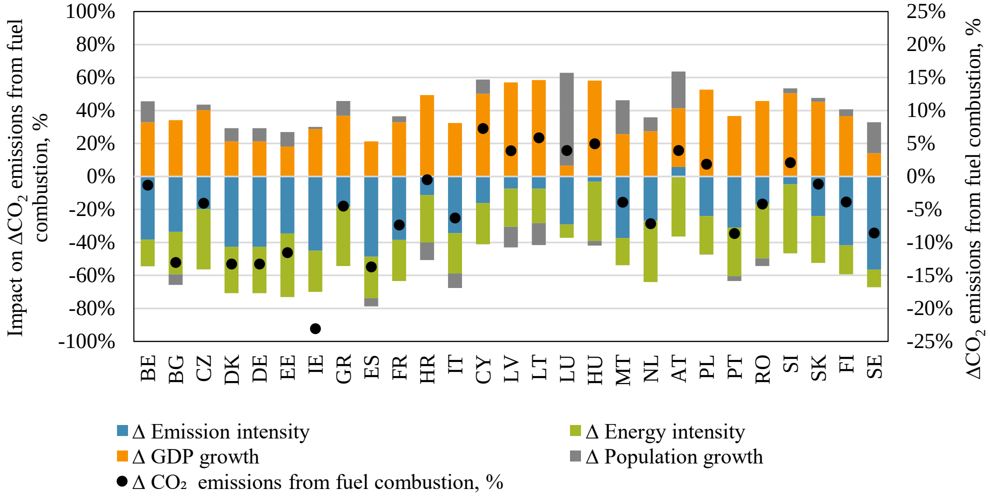

Fig. 3.11. LMDI results for changes in CO_2 emissions from fuel combustion from 2015 to 2019.

In Latvia, despite declining population growth, significant GDP growth was the main driver of the increase in CO_2 emissions from fuel combustion. Energy efficiency improvements did most to offset this trend, but not strongly enough. The transport and agriculture sectors were the main contributors to the overall increase in energy-related CO_2 emissions in Latvia.

The cross-country comparison of the combined LMDI and ESCI results shows alarming results for countries that rank high in the composite index of energy sustainability but show no or negative progress in reducing CO_2 emissions from fuel combustion over the five-year period from 2015 to 2019, such as Latvia and Austria. Both countries have a much higher share of renewable energy resources compared to other countries due to the initial hydropower plants that were installed in the past and, therefore, were initially among the countries with a higher share of renewable energy. The initial high position may have prevented a more active role in making additional investments and moving towards diversification of the existing power mix, for example, through wind energy.

3.3.2. LMDI decomposition analysis of renewable energy deployment over years

Fig. 3.12 illustrates the results of the LMDI decomposition analysis for EU countries and shows the contribution of each LMDI factor to the changes in gross electricity generation from RES in the period from 2012 to 2021. Latvia is the only country that experienced a decline in gross electricity generation from renewable energy sources by 392 GWh in 2021 when compared to 2012. This decrease can be largely attributed to fluctuations in hydropower generation, which heavily relies on weather conditions. In 2012, Latvia witnessed the second-largest peak in hydropower production over the past decade, driven by an exceptional surge in water inflow into the Daugava River, where the main hydropower plants are situated in the country.

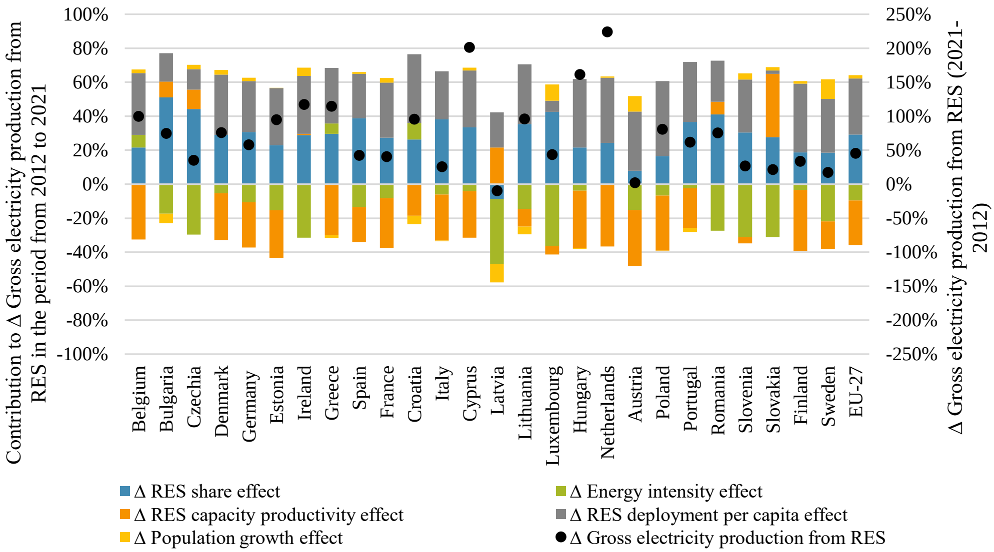

Fig. 3.12. Contribution of LMDI factors to changes in gross electricity production from RES over the period from 2012 to 2021.

For the EU-27, the main drivers were the RES deployment per capita effect and the RES share effect, which increased gross electricity generation from RES overall, while the negative RES capacity productivity effect and the negative energy intensity effect reduced gross electricity generation from RES. Population growth also contributed to the increase in RES-generated electricity, but the effect was not as significant as for the other factors. RES capacity productivity effect contributed negatively to gross electricity generation from RES in most countries except Bulgaria, the Czech Republic, Ireland, Latvia, Romania, and Slovakia. This observation suggests that economic growth is advancing at a faster rate in these countries compared to the growth of installed renewable energy capacities in comparison to other countries. Table 3.1 and Table 3.2 outline LMDI results for changes in gross electricity production in the Baltic States from wind and solar PV from 2012 to 2021, GWh

Table 3.1

LMDI Results for Changes in Gross Electricity Production from Wind from 2012 to 2021, GWh

	Estonia	**Latvia**	**Lithuania**
Δ Wind share	–193	31	195
Δ RES share	845	5	442
Δ Energy intensity	–551	–38	–140
Δ Wind capacity productivity	–1289	–4	–544
Δ Wind deployment per capita	1484	45	939
Δ Population growth	4	–11	–69
Δ Gross electricity production from wind	**299**	**27**	**822**

Table 3.2

LMDI Results for Changes in Gross Electricity Production from Solar PV from 2012 to 2021, GWh

	Estonia	Latvia	Lithuania
Δ Solar PV share	309	7	155
Δ RES share	50	1	29
Δ Energy intensity	–31	–1	–18
Δ Solar PV capacity productivity	–338	–7	–162
Δ Solar PV deployment per capita	363	7	189
Δ Population growth	1	0	–4
Δ Gross electricity production from PV	**354**	**7**	**189**

When compared to other Baltic States, Latvia's progress in expanding wind and solar PV capacities has been notably slow. In contrast, Lithuania and Estonia, which started with lower positions in their RES share in electricity production, have shown proactive efforts in increasing their wind and solar PV capacities. Latvia has relied more on hydropower plants for its renewable energy generation. This difference in approach has led to differing levels of progress in renewable energy capacity expansion among the Baltic States. Latvia's historical overemphasis on incumbent technologies might potentially hinder future RES growth. The growth of solar and wind capacities over 10 years in Latvia was so modest that it could not offset the fluctuating nature of hydropower-generated electricity.

3.3.3. LMDI decomposition analysis of energy imports

LMDI decomposition analysis is used to examine the changes in net energy imports in the EU-27. Fig. 3.13 illustrates the contribution of the LMDI decomposition analysis factors to the changes in EU-27 net energy imports for the period from 2015 to 2020, as well as the percentage change in total net energy imports over this period.

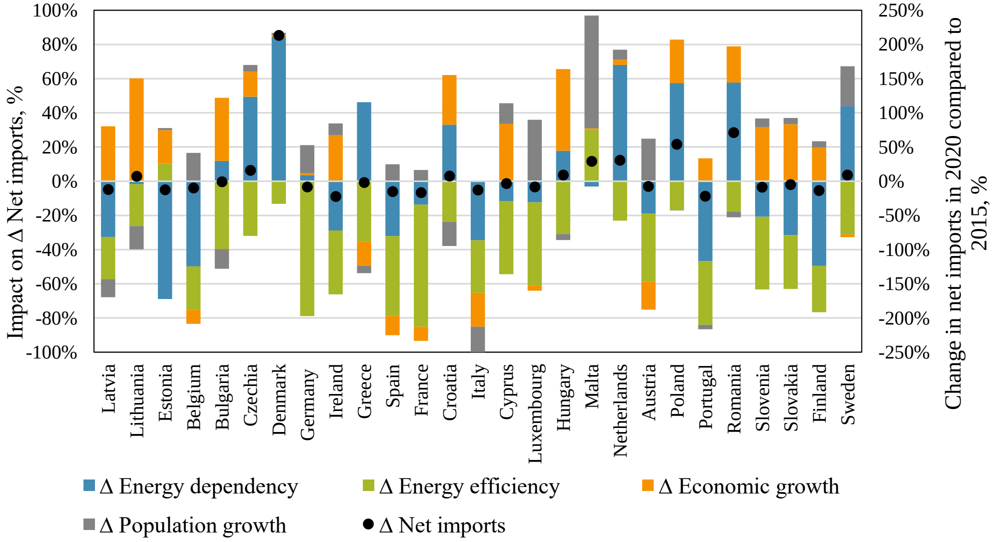

Fig. 3.13. Contribution of LMDI decomposition analysis factors to ΔNet imports for EU-27 in the period from 2015 to 2020.

The results show that the majority of EU-27 countries managed to reduce their net energy imports in the period from 2015 to 2020, with the exception of 9 countries that showed the opposite. The highest increases were recorded by Denmark (213.3 %), Romania (70.8 %), Poland (54.0 %), the Netherlands (30.6 %), and Malta (28.8 %). Other countries, such as the Czech Republic (15.9 %), Hungary (9.1 %), Sweden (9.0 %), Croatia (7.5 %), and Lithuania (6.9%), recorded lower increases in net energy imports during this period. All of these countries, with the exception of Malta and Lithuania, also showed significantly increased energy import dependency. On the other hand, some countries have succeeded in significantly reducing their dependence on imported energy in the period from 2015 to 2020. These countries include Latvia, Estonia, Belgium, Spain, France, Italy, Cyprus, Luxembourg, Austria, Portugal, Slovenia, Slovakia, and Finland.

The supply of natural gas and petroleum products is the main cornerstone for strengthening energy independence in almost all countries of the European Union. In 2020, natural gas accounted for almost a quarter (23.7 %) of gross available energy in the EU, with an import dependence of 83.6 %. In the EU, natural gas is mainly used for district heating and electricity generation. In 2020, Russia was the EU's main natural gas trading partner, and over the past decade, the EU's dependence on natural gas imports has increased from 71.6 % in 2011 to 83.6 % in 2020 [30], [31]. In countries with a high share of natural gas in the total energy mix, such as Italy (40 %), the Netherlands (38 %), Hungary (34 %), Ireland (33 %), Croatia (30 %), Germany (26 %), and Lithuania (25 %), where the share of natural gas in total gross available energy in 2020 is higher than the EU average of 24 %, serious restructuring of the energy system is needed [32]. In order to show the positions of each EU-27 country in terms of the level of energy import dependency and the share of renewable energy sources in total energy consumption, a correlation analysis is performed. Fig. 3.14 illustrates the relationship between the share of renewables in gross final energy consumption and energy import dependency in 2020 for all EU-27 countries.

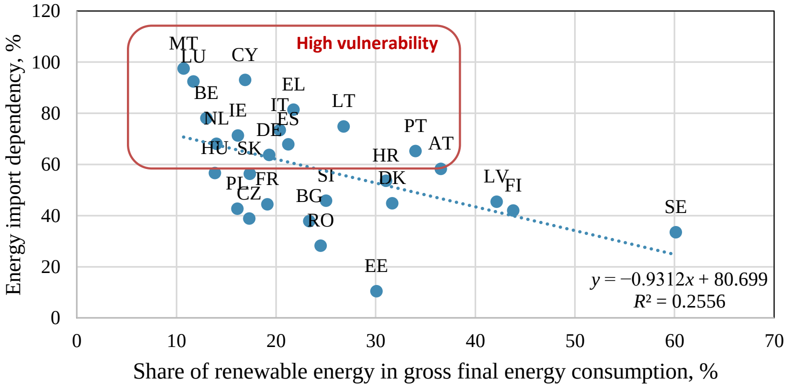

Fig. 3.14. Relationship between the share of renewable energy in gross final energy consumption and energy import dependency in 2020 for EU-27 countries.

The results show that for a number of countries that have a high energy import dependency, the share of renewable energy resources is also lower compared to other countries. This group of countries is particularly vulnerable to both the geopolitical situation and the consequences of climate change. The group of countries with high vulnerability includes Belgium, Greece, Lithuania, Italy, Ireland, the

Netherlands, Spain, Germany, Malta, Cyprus, and Luxembourg. However, Sweden shows the most competitive positions in terms of decarbonization of the energy system and national energy security.

3.4. Municipal energy system

3.4.1. Municipal energy transition index

The municipal energy transition index (ETI) was constructed to analyze and compare the energy system sustainability of five different municipalities in the Baltic Sea region – Gulbene (Latvia), Tukums (Latvia), Taurage (Lithuania), Tomelilla (Sweden), and Wejherowo (Poland). The results were grouped and described according to the values achieved in each dimension sub-index and the aggregated municipal energy transition index.

Fig. 3.15 illustrates the energy efficiency dimension sub-index results. Three main indicators described the energy efficiency dimension of selected municipalities – public building renovation trend (proportion of municipal buildings renovated from total heating area of buildings, %), infrastructure electricity consumption efficiency (municipal electricity consumption per inhabitant, kWh/inhabitant), public building heat consumption efficiency (average heat consumption of municipal buildings, kWh/m^2). The values of the energy efficiency dimension sub-index range from 0.77 (the highest, for Wejherowo) to 0.28 (the lowest, for Tukums), with an average benchmark value of 0.46.

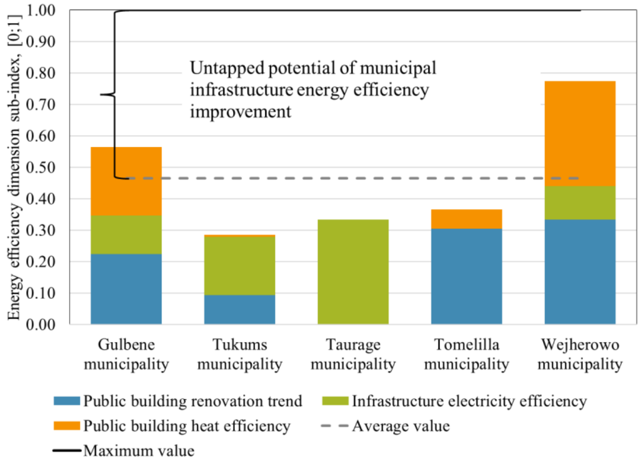

Fig. 3.15. Energy efficiency dimension sub-index results.

Fig. 3.16 illustrates the energy decarbonization dimension sub-index results. Three main indicators describe the energy decarbonization dimension of selected municipalities: RES power installation diffusion (installed municipal RES power plants MW per inhabitant), RES heat share (share of produced heat energy from renewable energy resources, %), and transport decarbonization (share of electrical and alternative fuel transportation, %). Energy decarbonization dimension sub-index values indicated the highest range in the achieved results for the municipalities, with the highest value of 0.92 (Tomelilla municipality) and the lowest of 0.08 (Wejherowo municipality).

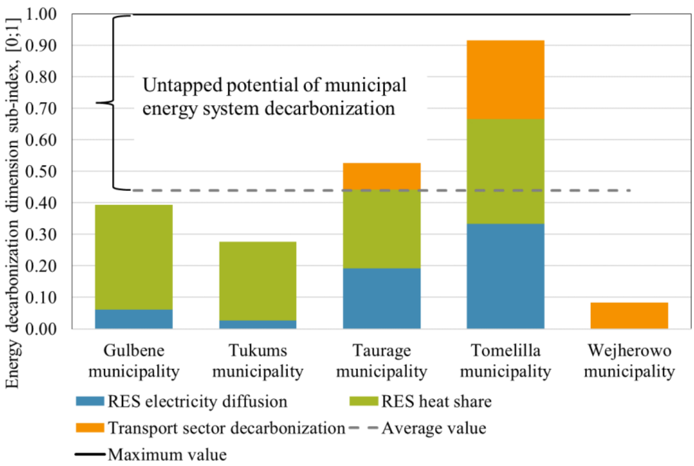

Fig. 3.16. Energy decarbonization dimension sub-index results.

Fig. 3.17 illustrates the smart energy system dimension sub-index results. Three main qualitative assessment indicators describe the smart energy system dimension of selected municipalities: digitalization and energy monitoring data accessibility (level of data quality and complexity of energy data collection), energy storage deployment (existing RES storage technologies installed), innovation acceptance level (considerations of innovation adaptation such as hydrogen, and its derivatives). The smart energy system dimension sub-index results, with an average benchmark score of 0.32, were significantly lower than in other dimensions, representing higher untapped potential. The values ranged from 0.42, the highest for Gulbene and Wejherowo municipalities and the lowest with 0.25 for Tukums, Taurage and Tomelilla municipalities.

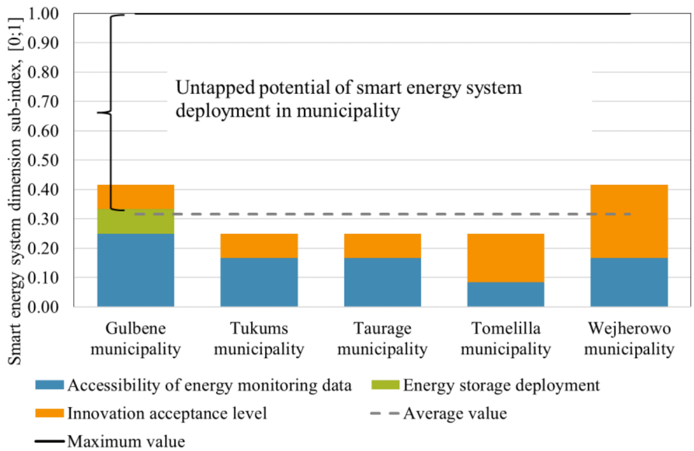

Fig. 3.17. Smart energy system dimension sub-index results.

Fig. 3.18 illustrates the aggregated results for the municipal energy transition index (ETI) of the selected municipalities. All municipalities show major untapped potential for sustainable municipal energy transition, given that the maximum index value is equal to 1.

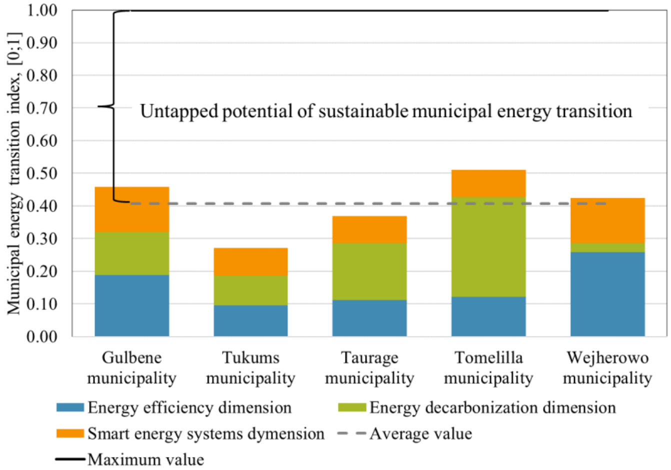

Fig. 3.18. Municipal energy transition index (*ETI*) results.

The results highlight various challenges of the municipal energy transition. Transport decarbonization is a major issue for the majority of municipalities with a low share of renewable energy. The results show that there is significant untapped potential for the installation of RE power plants in all municipalities, taking into account that surplus electricity could be combined with integrated energy storage solutions or through the production of hydrogen. The majority of municipalities are still reluctant when it comes to innovations such as the use of hydrogen and its derivatives. There is still a great deal of uncertainty that affects municipalities' confidence in decision-making regarding the potential use of hydrogen. Low energy efficiency is still a major issue in some municipalities. The renovation rate of municipal buildings and heat consumption could be significantly improved by actively investing in energy efficiency measures.

3.4.2. Energy storage technologies in local energy systems using PESTLE analysis

Nineteen indicators grouped into six main dimensions, such as political, economic, social, technological, legal, and environmental, were used to evaluate and compare the selected renewable energy storage alternatives in a municipal context. The results first represent the values of the sub-indices of the dimensions (see Fig. 3.19). Then, the results of the sub-indices were combined into the PESTLE composite index, which is illustrated in Fig. 3.20.

The analysis of the political dimension has shown that political initiative and support from the state, targeted policies at the national and international levels, and the identification of specific municipal priorities and needs are the key factors for the potential deployment of energy storage technologies. Currently, thermal energy storage and battery integration are a higher priority for the government, and as a result, there are national funding programs that support the development of such infrastructure in municipalities. However, there is no clear policy focus or support to accelerate the deployment of hydrogen or biomethane systems in municipalities.

The analysis of the economic dimension showed that thermal energy storage and batteries are currently the most cost-effective alternative, as they have the lowest specific capital investment costs (EUR/kW) and operation and maintenance costs (EUR/kWh) compared to hydrogen and biomethane, which require high investments in the construction of necessary infrastructure. In addition, the capital availability in terms of municipal co-financing for batteries and thermal energy storage is much higher, as the initial investment costs are lower.

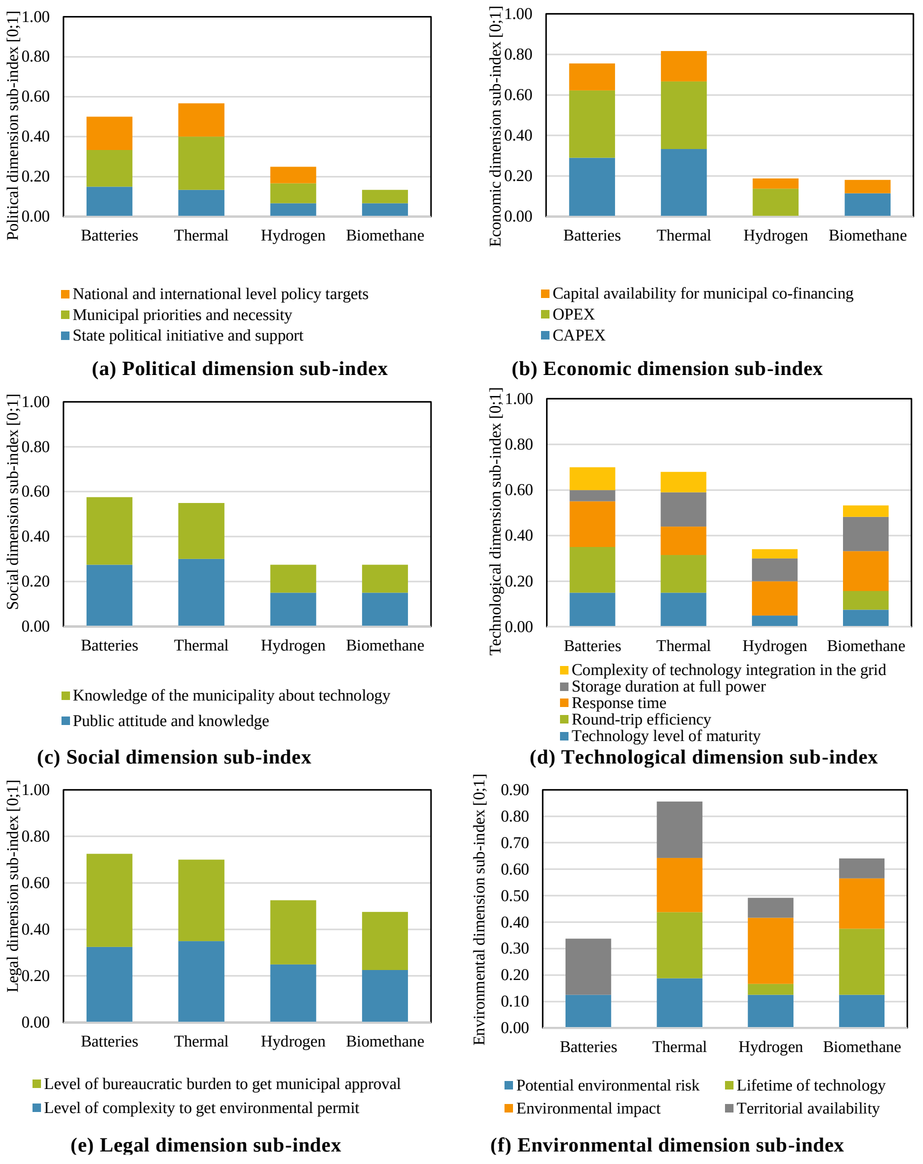

Fig. 3.19. Sub-indices of PESTLE dimensions.

The analysis of the social dimension revealed that both the public's and the municipality's attitudes and knowledge about the selected technologies are higher and more positive in the case of thermal energy storage and batteries, with which they are already familiar. However, the general public and the municipality are quite skeptical about the potential pathways to hydrogen and biomethane, as there is still a lot unknown about these technologies, and the municipality does not have the necessary skills and knowledge to confidently understand how these systems work and how they could potentially be integrated into the municipal energy system.

The results of the technological dimension have shown that batteries and thermal energy storage currently outperform hydrogen and biomethane storage due to higher technological maturity, round-trip efficiency, and lower complexity of the technology to be integrated into the existing grid. While batteries showed the fastest response time among the other alternatives, their storage duration at full power was significantly lower than for thermal energy storage, hydrogen, and biomethane.

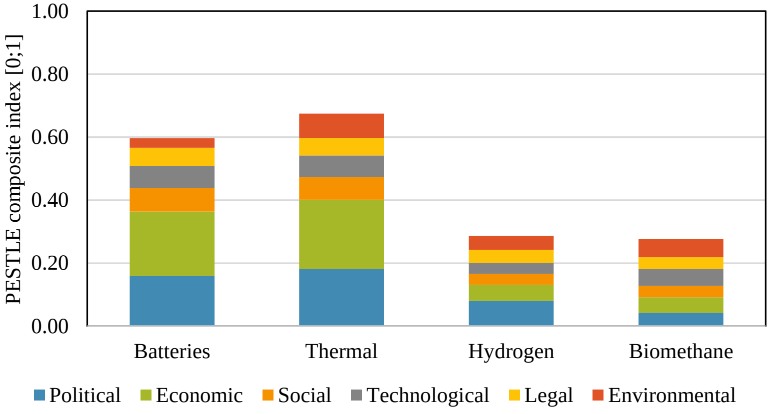

Fig. 3.20. PESTLE composite index results.

The legal dimension evaluated the degree of complexity required to obtain an environmental permit and the degree of bureaucracy to obtain a municipal permit for all four alternative technologies. The results showed that for hydrogen and biomethane, the approval process would be significantly more complicated due to the safety risks and many uncertainties of these technologies, which could potentially delay the overall process of deploying these technologies in the municipality.

The results of the environmental dimension showed that batteries have the greatest potential environmental impact compared to other alternatives. This is due to the lithium-ion resource, which is very energy intensive to extract, and the disposal of lithium-ion batteries is associated with several sustainability issues. Batteries also have the shortest lifespan compared to other alternatives, which requires more frequent replacement of technical components and has a negative impact on resource efficiency.

The overall PESTLE composite index results show that thermal energy storage reached the highest composite index value of 0.67, followed by batteries with 0.60, hydrogen with 0.29 and biomethane with 0.28. The study concluded that thermal energy storage and lithium-ion batteries are the most viable energy storage options for municipalities in Latvia due to their cost-effectiveness, technological maturity, and higher public acceptance, supported by national funding programs. In contrast, hydrogen and biomethane systems face significant economic, legal, and social challenges, including high investment costs, bureaucratic issues, and limited familiarity, making their integration less feasible in the current context, which might change in future.

3.4.3. Stakeholder perspectives through fuzzy cognitive mapping

Fuzzy cognitive mapping (FCM) methodology was used to analyze the mental models of different stakeholders regarding their perceived importance of different factors influencing the implementation of energy storage in municipalities. The results revealed significant differences in the mental models developed by the energy experts, researchers, and stakeholder groups. To determine the categories that have the highest impact on energy storage deployment in the local energy system, the centrality index was calculated for each category. Fig. 3.21 illustrates the centrality profile for each group – energy experts, researchers and local energy transition stakeholders.

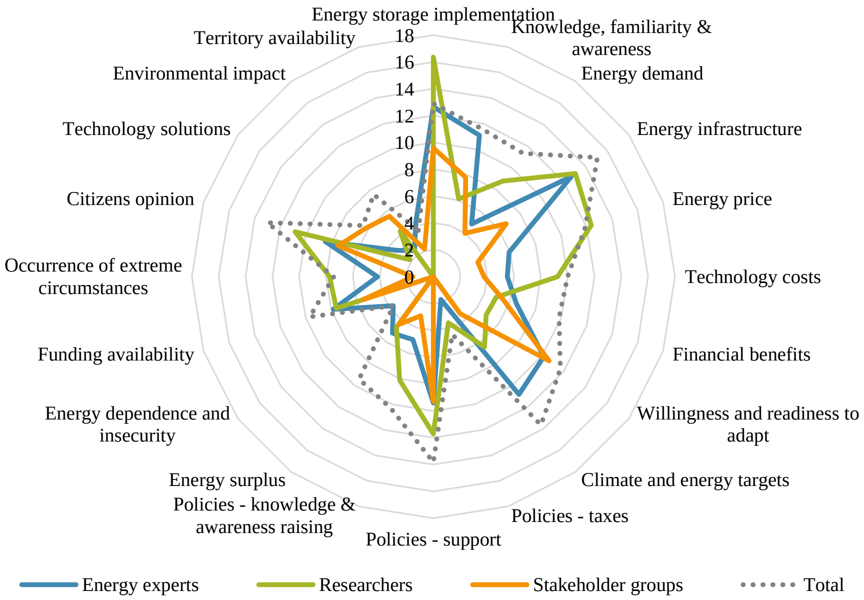

Fig. 3.21. Centrality profiles of defined categories.

For energy experts, the most central categories were energy infrastructure and energy storage implementation, knowledge, familiarity and awareness, climate and energy targets, and willingness and readiness to adapt. Similarly, for researchers, energy infrastructure and energy storage implementation were the most central elements, followed by energy price and support policies. Whereas for local energy transition stakeholders, the most central categories were willingness and readiness to adapt, energy storage implementation, support policies, knowledge, familiarity and awareness, and citizens' opinion. Overall, municipalities and local energy transition stakeholders are placing greater emphasis on the role of knowledge, management will and government support measures, which are seen as the key to action. It can be concluded that the current challenges are related to a lack of knowledge and willingness to adapt to new solutions, which in turn could be eliminated by adequate policies to support this transition of local authorities. Similarly, energy experts acknowledged knowledge, familiarity and awareness as one of the most important factors influencing energy storage deployment in local energy infrastructures. However, researchers emphasize energy price and support policies as the key drivers for change.

While factors vary, support schemes such as subsidies, knowledge and awareness-raising campaigns emerge as a central focus across stakeholder groups. Moreover, mental model designs revealed that municipalities address challenges linearly, failing to foresee the important interconnections between different factors, while energy experts think in feedback loops and overall system requirements. The study reveals that there should be a common ground for a shared understanding to drive robust policy and infrastructure development. Enhancing comprehension of the specific perceptions and requirements of diverse stakeholders involved in the deployment of renewable energy storage infrastructure can significantly impact their engagement in policy-making and investment activities. It is essential to engage in targeted communication with local public authorities, emphasizing the benefits of energy storage in terms of improved system independence and potential cost savings on energy in the long run. This approach can positively influence public opinion and contribute to the legitimacy of successful energy policies. Furthermore, the findings highlight the need for more direct and straightforward communication with local public authorities. More detailed research with the possible development of a system dynamics model is needed to develop specific strategies that could be applied in communication with different stakeholders to accelerate the deployment of energy storage in local energy transitions.

3.5. Climate and energy policy

3.5.1. Kaya identity for GHG driver analysis and climate policy forecasting

Kaya identity with LMDI decomposition analysis is conducted for the EU-28 (including the UK) countries for a 10-year study period from 2010 to 2019 to study the main drivers of changes in GHG emissions and estimate the progress made in implementing the Green Deal targets. The results are shown in Fig. 3.22.

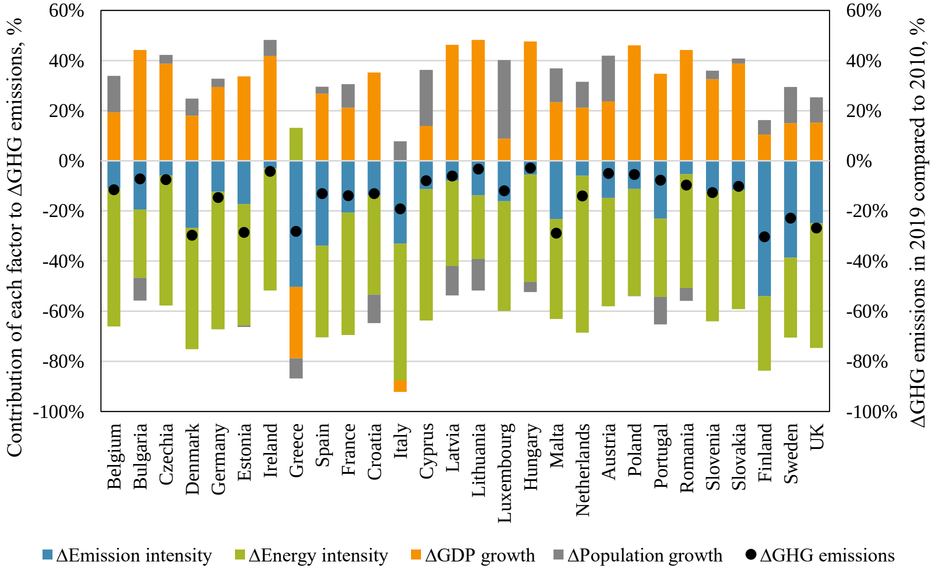

Fig. 3.22. Kaya identity decomposition for the EU-28 countries.

All countries have been able to reduce the amounts of GHG emissions over the last decade when comparing GHG emission levels in 2019 with those in 2010. The most significant change in GHG emissions was observed in Denmark (–30 %), Finland (–30 %), and Estonia (–29 %), indicating the greatest progress in reducing GHG emissions. In contrast, Lithuania (–3 %), Hungary (–3 %), and Ireland (–4 %) showed the smallest decrease in GHG emissions compared to the other countries. In terms of absolute changes, the highest reduction was achieved by the UK (164 Mt CO_2 eq.) and Germany (137 Mt CO_2 eq.), representing a change in GHG emissions of 27 % and 15 %, respectively.

In Latvia (Fig. 3.23), an overall decrease of 0.74 million tons of CO_2 equivalent emissions was achieved over the 10-year period from 2010 to 2019. The decrease in absolute GHG emissions was mainly caused by a significant decrease in energy intensity (–3.33). The decrease in emission intensity (–0.76) and the decrease in population (–1.14) also contributed to the reduction in GHG emissions. Energy efficiency measures in Latvia were found to be the most effective drivers of GHG emission reductions. In fact, energy efficiency measures had more than four times the effect on reducing GHG emissions as improvements in emissions intensity.

The larger decrease in emissions in Latvia was offset by growing economic activity, where GDP growth (4.48) drove up GHG emissions and significantly hindered the overall pace of emissions reductions. Moreover, in the years when GDP grew significantly, as observed in 2015, 2017 and 2018, the lack of measures to improve energy and emissions intensity led to an increase in GHG emissions. The dynamics of annual changes in decomposition factors show that in the period from 2013 to 2016, when the total amount of energy generated from hydropower decreased by more than one-third compared to 2012, the emission intensity factor increased significantly, signaling an increase in specific GHG emissions. The same relationship can be observed in 2017, when hydropower plants generated a record high amount of energy from hydropower, which is reflected in a significant decrease in emission intensity in this representative year. Therefore, given the large share of hydropower in the overall Latvian energy mix, it can be concluded that fluctuations in the amount of energy generated from hydropower undoubtedly affect the overall emission intensity.

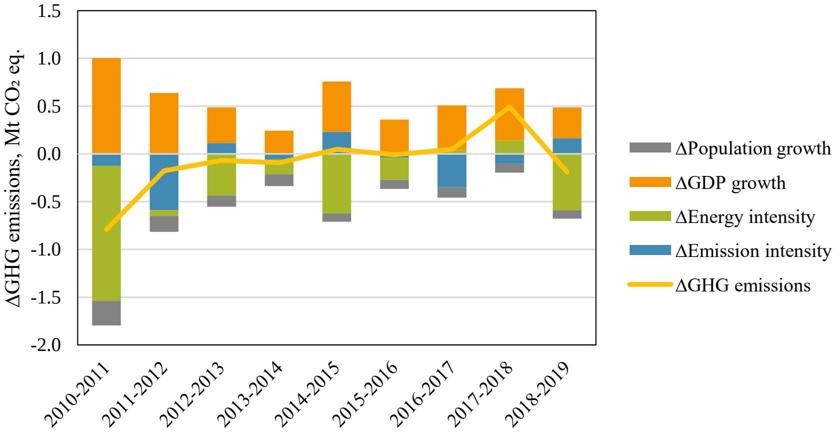

Fig. 3.23. Year-to-year Kaya identity decomposition for Latvia.

The results of the LMDI decomposition analysis are further used to predict future trajectories for changes in GHG emissions in Latvia (see Fig. 3.24). Under the existing measures scenario, Latvia is projected to emit 11.2 Mt CO_2-eq by 2030. As Latvia has announced its GHG emission target of 9.2 Mt CO_2 eq. by 2030, the projected values show that the current GHG reduction measures are not sufficient to achieve the target. The predicted results for Latvia show that greater efforts should be made to reach the target. It is projected that if no climate policy measures are taken and the Latvian economy operates under the "business as usual" scenario, total GHG emissions will increase by 13 % in 2030 compared to 2019 levels.

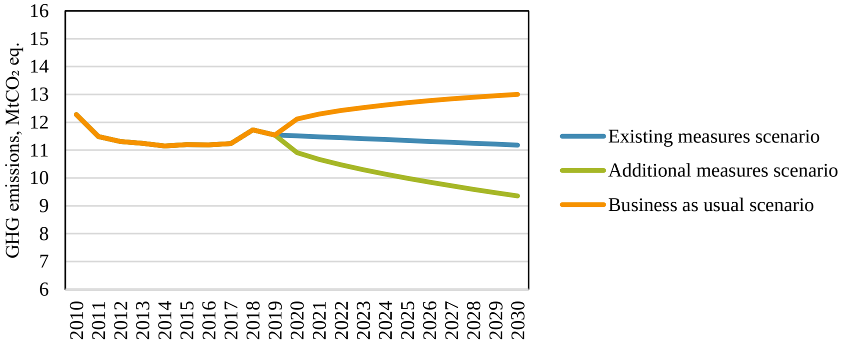

Fig. 3.24. Forecasts of GHG emissions for Latvia.

The forecast of GHG emissions for Latvia shows that current climate policies are not sufficient to achieve the 2030 GHG emission reduction targets set in the National Energy and Climate Plan (NECP). Therefore, additional measures should be taken to enforce GHG emission reductions in all resource-consuming sectors. The lack of sector-specific targets in existing national climate policies and goals could be one of the cornerstones for achieving greater carbon reductions. Specific targets and commitments should be set separately for the transport, industry, services, agriculture and household sectors in order to construct more effective long-term energy and climate policies.

3.5.2. Policy risk due diligence framework

A risk matrix framework combined with a composite index methodology was applied to produce a risk index composed of 24 risk indicators grouped into six main risk categories – political, technical, economic, environmental, social and administrative. The consistency and effectiveness of the model were validated in the five case studies of the Latvian climate and energy policy. Case 1 involved ex ante evaluation for wind energy park construction. Case 2 was related to ex post evaluation of the Energy Efficiency Monitoring System program, a policy instrument that was established in Latvia in 2017 by the Ministry of Economics of the Republic of Latvia. Case 3 included ex post assessment of the climate financial instrument (CCFI), a Latvian state budget program that was in force in the period from 2009 to 2015 and was administrated by the Ministry of the Environmental Protection and Regional Development of the Republic of Latvia. Cases 4 and 5 addressed the theoretical ex ante challenge of decentralized or centralized energy system development. Fig. 3.25 illustrates the comparison of the sub-index values determined for the different policy instruments examined.

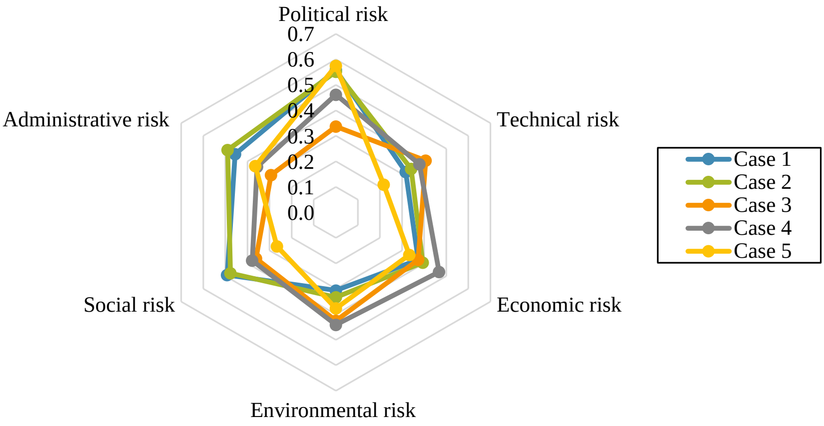

Fig. 3.25. The values of risk sub-indices from the case study evaluations.

The highest overall risk index value of 0.43 was achieved by the energy efficiency system monitoring program (Case 2), with the main reasons being delayed implementation, inadequate policy design, unclear guidelines, and weak long-term vision. The second highest risk index value of 0.42 was reported for the construction of a wind energy park (Case 1), mainly due to insufficient information dissemination, low public acceptance, unclear regulations, political resistance, and bureaucratic struggles, all hindering implementation and expansion. The development of centralized energy generation (Case 5) had the lowest total risk index (0.36) but faced the highest political risk due to policy instability and weak long-term planning, while distributed energy generation (Case 4) had a higher overall risk index (0.41) driven by significant economic risks, including inefficiencies and insufficient fiscal policies in place. The second lowest risk index value of 0.37 was found for the climate finance instrument (Case 3), but this policy faced the highest environmental risk sub-index and failed to achieve its main objective of reducing GHG emissions, indicating a significant contradiction in its policy design and implementation.

CONCLUSIONS

The hypothesis of this Thesis is confirmed as the methods (i.e., composite index, decomposition analysis and fuzzy cognitive mapping) developed and approbated during the Thesis have proven to be highly effective in providing valuable insights into various levels of energy systems.

The overall findings on energy sustainability assessment reveal that Latvia's historical reliance on hydropower has created a naive sense of comfort and sufficiency, delaying more proactive efforts to expand wind and solar capacities.

Enhancing system flexibility and focusing on energy storage solutions will play a major role in transforming renewable energy supply potential into reality. Lithium-ion batteries and thermal energy storage appear to be the most viable now, but hydrogen and biomethane emerge as future solutions.

Municipalities are regarded as the primary drivers and change agents of the EU's path to climate neutrality. However, there are significant challenges in transport decarbonization, renewable adoption, and energy efficiency improvements in local energy systems.

Growing economic activity in lower-income countries was the main offsetting factor hindering the achievement of larger reductions in GHG emissions. In the Baltics, current climate policies are not sufficient to achieve the set 2030 GHG emission reduction targets. There is a lack of sector-specific targets in existing policies. In industry, sectoral heterogeneity should be taken into account to design tailored policies. There might be different incentives between high-intensity sectors and low-intensity sectors. Identified measures to advance transport decarbonization are (1) public transport development; (2) expansion of electric and alternative fuel infrastructure; and (3) enhancement of energy efficiency.

A carefully designed climate policy is the main cornerstone in order to turn ambitious commitments into determined actions. This Thesis offers a due diligence framework to identify and address critical areas in policies to help avoid failures.

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