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ENERGY SUSTAINABILITY ASSESSMENT METHODS TOWARDS EUROPEAN GREEN DEAL TRANSITION

Doctoral Thesis

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ANNOTATION

The European Union has committed to become a climate-neutral continent by 2050 with a first mid-term target to achieve at least 55% emission cut by 2030. Rapid decarbonization is needed to achieve these ambitious goals with a special focus on the energy sector since it is the largest source of GHG emissions not only globally but also in the EU and Latvia. Latvia's energy sector is facing turbulent times as it strives to strengthen energy independence while ensuring affordability and sustainability for all. The newly published Latvian Energy Strategy 2050 emphasizes increasing self-sufficiency and increasing renewable energy, yet the energy sector remains heavily reliant on its Soviet-era heritage of hydropower infrastructure. Moreover, transitioning to a future low-carbon energy system with a significant share of renewables requires innovative flexibility measures, moving beyond historical dependence on natural gas co-generation plants for grid stabilization. The decisions made today will define the pace and effectiveness of Latvia's energy transition. Latvia should learn from more advanced and successful energy policies in other EU countries to transform strategic plans to reasonable actions that support sustainable transition.

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. A novel energy sustainability assessment model is developed, combining several unique methods such as decomposition analysis, composite index methodology, PESTLE analysis, fuzzy cognitive mapping, the Kaya identity equation, and policy risk due diligence framework. These methods analyze energy systems at sectoral (including industry and transport), local (with a focus on municipal energy system scale), national, and international (EU-27) levels. Using a multidisciplinary and benchmarking approach, this Thesis compares development of the Latvian energy system with that of the EU-27 countries, offering valuable insights to guide energy sector stakeholders, policy developers and decision-makers.

This Doctoral Thesis is based on a set of 12 thematically unified scientific publications. It compiles the key insights from the published scientific articles developed during the course of doctoral studies.

This Thesis consists 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 Thesis aim and hypothesis, describes research topicality, novelty, practical significance, and overall Thesis structure. The first section includes a literature review of the existing climate and energy policy governing the long-term development of the energy sector and background information on Latvia's energy system characteristics in comparison to EU-27. The second section of the Thesis 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. The third section includes the results and discussion section, which is structured as journey of 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 aforementioned methods. Thesis is finalized by compilation of key research conclusions.

This Doctoral Thesis is written in English, it comprises 296 pages including appendices and includes 41 figures, 36 tables, 29 equations, and 166 references.

ANOTĀCIJA

Eiropas Savienība ir apņēmusies līdz 2050.gadam kļūt par klimatneitrālu kontinentu, kas ietver starpposma mērķi līdz 2030.gadam samazināt emisijas par vismaz 55%. Lai sasniegtu šos ambiciozos mērķus, ir nepieciešama strauja dekarbonizācija, īpašu uzmanību pievēršot enerģētikas sektoram, kas ir lielākais SEG emisiju avots ne tikai globāli, bet arī Eiropas Savienībā un Latvijā. Latvijas enerģētikas sektors saskaras ar neskaitāmiem izaicinājumiem, meklējot risinājumus enerģētiskās neatkarības stiprināšanai, vienlaikus nodrošinot pieejamu un ilgtspējīgu enerģiju visiem. Nesen publicētā Latvijas Enerģētikas stratēģija līdz 2050.gadam uzsver enerģētiskās pašpietiekamības un atjaunojamās enerģijas īpatsvara paaugstināšanu, tomēr Latvijas energosektors joprojām lielā mērā ir atkarīgs no Padomju laika mantotās hidroelektrostaciju infrastruktūras. Turklāt pāreja uz zema oglekļa emisiju nākotnes enerģētikas sistēmu ar būtisku atjaunojamās enerģijas īpatsvaru pieprasa inovācijas energosektora elastības veicināšanai, kas būtu kas vairāk par vēsturisko atkarību no dabasgāzes koģenerācijas stacijām tīkla stabilizēšanai. Šodien pieņemtie lēmumi noteiks Latvijas enerģētikas pārejas tempu un efektivitāti. Latvijai būtu jāņem piemērs no citām ES valstīm ar progresīvākām un veiksmīgākām enerģētikas politikām, lai stratēģiskos plānus pārvērstu pamatotos pasākumos, kas atbalsta ilgtspējīgu enerģētikas sektora pāreju.

Darba mērķis ir izstrādāt visaptverošu enerģētikas ilgtspējas novērtēšanas modeli, kas identificē galvenos virzītājspēkus un izaicinājumus Latvijas enerģētikas ceļā uz klimatneitralitāti Eiropas Zaļā kursa un REPowerEU politikas konteksta ietvaros. Darba ietvaros tiek izstrādāts inovatīvs enerģētikas ilgtspējas novērtēšanas modelis, kas apvieno vairākas unikālas metodes, tostarp dekompozīcijas analīzi, saliktā indeksa metodoloģiju, PESTLE analīzi, kognitīvās kartēšanas metodi, Kaya identitātes vienādojumu un politikas riska novērtēšanas ietvaru. Šīs metodes tiek izmantotas enerģētikas sistēmu analīzei dažādos līmeņos: sektora (ieskaitot rūpniecību un transportu), vietējā (ar uzsvaru uz pašvaldību enerģētikas sistēmām), nacionālā un starptautiskā (ES-27) līmenī. Izmantojot starpdisciplināru un līmeņatzīmju pieeju, šī darba ietvaros Latvijas enerģētikas sistēmas attīstība tiek salīdzināta ar ES-27 valstīm, sniedzot vērtīgus ieskatus, kas var kalpot par ceļvedi enerģētikas nozares dalībniekiem, politikas veidotājiem un lēmumu pieņēmējiem.

Promocijas darbs ir veidots kā publikācijas kopa, kas balstās uz 12 tematiski vienotām zinātniskajām publikācijām, kas izstrādātas doktorantūras studiju ietvaros. Darbs sastāv no ievada un četrām galvenajām nodaļām: (1) literatūras analīze, (2) pētījuma metodikas, (3) rezultāti un diskusija, un (4) secinājumi. Ievada sadaļā ir izklāstīts darba mērķis un hipotēze, aprakstīta pētījuma aktualitāte, novitāte, praktiskā nozīme un darba struktūra. Pirmajā nodaļā ir aprakstīta literatūras analīze par esošo klimata un enerģētikas politiku, kas regulē enerģētikas nozares ilgtermiņa attīstību, kā arī statistiskais apkopojums par Latvijas enerģētikas sistēmas raksturojumu salīdzinājumā ar ES-27. Otrajā nodaļā aprakstītas izmantotās pētniecības metodes, iezīmējot galvenās pieejas saliktā indeksa, dekompozīcijas analīzes un kognitīvās kartēšanas metodes izstrādē. Trešā nodaļa ietver rezultātu un diskusijas aprakstu, kas strukturēta kā ceļojums cauri enerģētikas sektora attīstībai caur vēsturi uz nākotni, tiecoties uz pakāpenisku emisiju samazināšanu un ilgtspējas kāpināšanu, kas tiek analizēta, izmantojot iepriekš minētās metodes. Darbs noslēdzas ar galveno pētījuma secinājumu apkopošanu.

Šis promocijas darbs ir izstrādāts angļu valodā, tas sastāv no 296 lapaspusēm, iekļaujot pielikumus, ietver 41 attēlu, 36 tabulas, 29 vienādojumus un 166 atsauces.

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I am also grateful to my colleagues at the Institute of Institute of Energy Systems and Environment, whose inspiration and motivation have taught me never to give up. I truly appreciate the fact that I could always turn to them for help, words of encouragement, and valuable suggestions, which allowed me to move forward and achieve even better results through our collective efforts.

Above all, I want to extend my heartfelt thanks to my family, my partner Edgars, and our beloved dog Shiro 🐾. Their love, care, and unwavering support have been invaluable throughout these years of studies. Thank you for always creating an environment that allowed me to focus on my work without distractions and for being there whenever I needed support and encouragement the most.

TABLE OF CONTENTS

ABBREVIATIONS

EU - European Union
EU-27 - All 27 EU member states
UN – United Nations
GHG - Greenhouse gases
RES - Renewable energy sources
NDC - Nationally determined contribution
NECP - National Energy and Climate Plan
PV - Photovoltaics
GDP - Gross domestic product
LULUCF - Land Use, Land-Use Change and Forestry
CI - Composite index
EEI - Energy Efficiency Index
ETI - Energy transition index
LMDI - Log-Mean Divisia Index
FCM - Fuzzy cognitive mapping
CAPEX - Capital expenditure
OPEX - Operating expense
CCFI - Climate financial instrument
NACE Rev. 2 - Statistical classification of economic activities
CSB - Central Statistical Bureau of Latvia
IEA - International Energy Agency
IPCC - Intergovernmental Panel on Climate Change
UNFCCC - United Nations Framework Convention on Climate Change
CLRTAP - Convention on Long-Range Transboundary Air Pollution
CNG - Compressed natural gas
CAGR - Compound annual growth rate

INTRODUCTION

The global economy is on the verge of one of the greatest transitions in modern history. The ability to strengthen national securities, ensure sustainable economic development and prosperity while significantly reducing the 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.

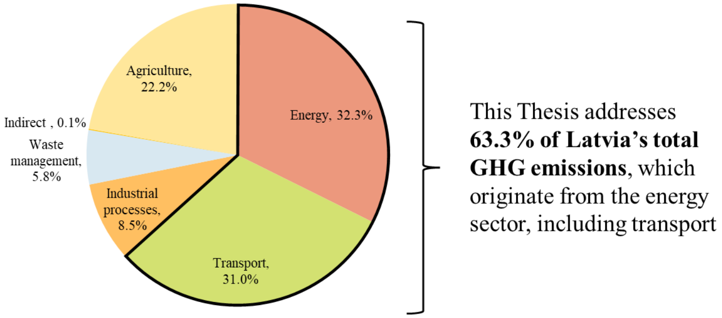
In the European Union (EU), the energy sector accounts for more than 75% of the EU’s greenhouse gas emissions [1], plays a crucial role in driving economic growth, is a primary factor behind the rising cost of living [2], and serves as a cornerstone for enhancing security. Nowadays, the future of energy transition 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 European Union 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].



This Thesis addresses **63.3% of Latvia’s total GHG emissions**, which originate from the energy sector, including transport

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.

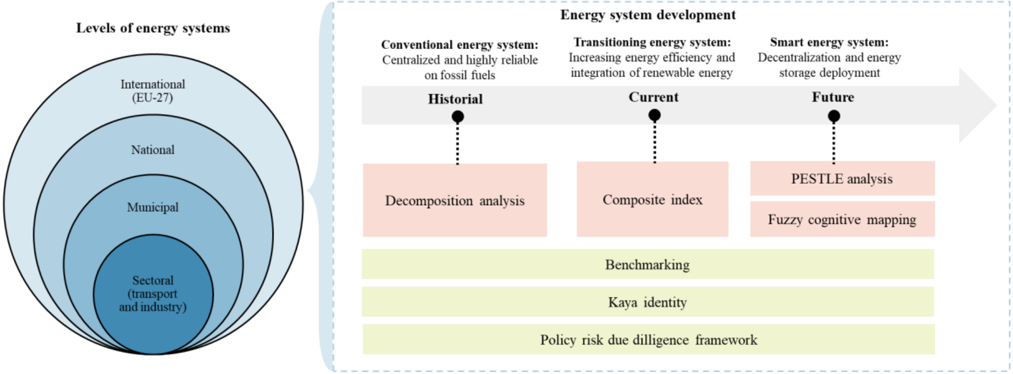


Fig. 2. Research framework and scientific novelty of the Thesis.

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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9. Dolge, K., Vičmane, L.K, Bohvalovs, Ģ., Blumberga, D. Are BSR Municipalities on Track for Energy Transition? *International Scientific Conference of Environmental and Climate Technologies CONECT 2024*, Riga, Latvia, May 15-17, 2024.

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.

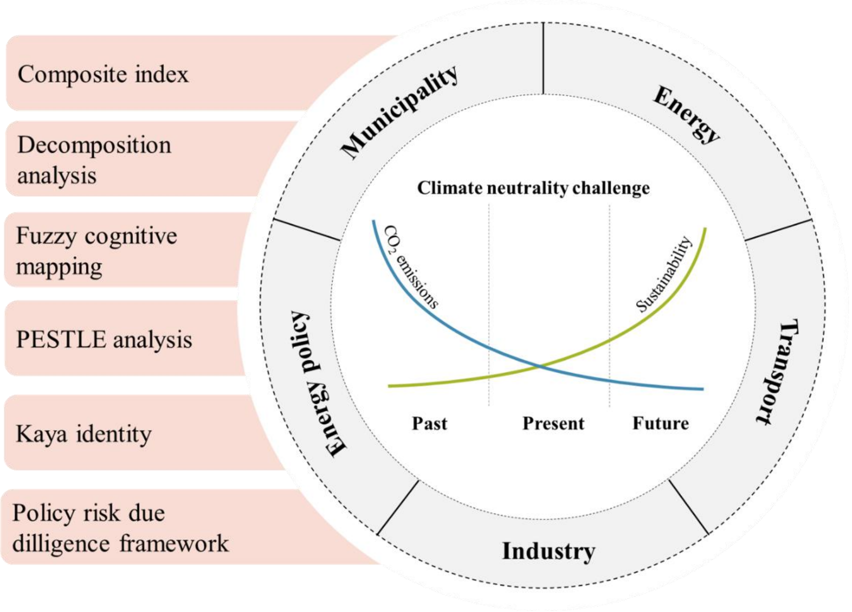


Fig. 3. Structure of the Thesis results.

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, Thesis novelty and practical significance. It presents the Thesis aim and hypothesis, as well as outlines the approbation of the published research results.

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.

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.

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

Climate change policy and the economy

UN’s Emissions Gap Report 2024 estimates that current nationally determined contributions (NDCs) lacks ambition and are off track to meet global climate change targets set at the Paris Agreement. The latest projections show that if no stringent improvements in commitments and actions towards national climate change mitigation measures are made then existing national commitments will increase global warming by 2.6-3ºC by the end of the 21st century [9]. It signals that the current pace of progress in mitigating climate change is not fast enough to achieve the ambitious targets.

To get on track of 1.5ºC it is estimated that the amount of emissions should decrease by at least 42% by 2030 and 57% by 2035 compared to 2019 emission levels [9]. Any delay in reducing emissions will require even more serious and costly measures in the future and could entail serious institutional, socio-economic, infrastructural and structural risks [10]. European Central Bank’s study concluded that the impact of climate change on the EU economy is significant, affecting all major economic sectors such as agriculture and fisheries, industry, energy, tourism, and many others. It is estimated that real GDP would decrease by 2-10% by 2100 if no additional measures are taken to mitigate climate change and temperatures rise [11]. Climate change poses a major challenge to capitalist-oriented societies to restructure their economies and adapt to low-carbon measures that, at first glance, may not be the most economically viable option. Therefore, climate-economy models have become increasingly important in environmental and energy policy in recent years.

To raise the urgency and narrow the identified emission gap, the European Green Deal has set ambitious net-zero emissions targets by 2050. This commitment implies reducing GHG emissions by at least 55% by 2030, compared to 1990 levels [12]. To reach the collective target, each EU member state is responsible for making a major contribution to achieving greater GHG emission reductions. The 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 [13]. The complexity of this dual relationship between climate change measures and economic growth puts additional pressure on member states that need to lead the shift towards adaptation of sustainable economies.

Energy transition policy targets

Since the energy sector accounts for the vast majority of the EU’s greenhouse gas emissions [1], achieving these ambitious climate targets will require 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 [14].

As the EU strives for rapid decarbonization and electrification of its energy system, the EU's electricity system faces significant challenges. The European Commission projects that the share of renewable energy in electricity generation should reach 55% in 2025 and 72% in 2030 [15], more than doubling its current level of 33% in 2021 [16].

These projections indicate that as smart energy systems continue to evolve, in the future there will be a substantial increase in the electrification of end-use consumption. 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 by transitioning to vehicles that utilize electricity as an alternative fuel source [17]. EU’s electricity sector is expected to grow significantly in the next years [18], as it is expected that the electricity demand in the EU will increase by at least 32% by 2050 compared to its current levels [19]. 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 [20]. The REPowerEU plan is intended to address all aspects of the energy trilemma that determines national energy systems in order to ensure that sufficient efforts are placed on decreasing fossil energy import dependence from Russia while delivering energy at an affordable price to end-consumers [21]. REPower EU plans to increase Europe's energy independence and end fossil energy imports from Russia before 2030 by promoting the implementation of energy efficiency measures, diversifying current energy suppliers, and accelerate the use of RES by exploiting the maximum potential of local RES to compensate for Russian energy imports and support Europe's energy independence [22]. The role of renewable energy use in electricity generation is highlighted in REPowerEU plan, which has set a target for the share of renewable energy in gross final electricity consumption to reach 69% by 2030 [23], compared to only 37.6% of total electricity demand in the EU from renewable sources in 2021 [24].

Role of energy storage in strengthening system flexibility

The rising utilisation of renewable energy sources presents energy system operators with significant challenges, since the switch to these variable sources requires a larger degree of flexibility and introduces more complexities into energy system infrastructures [25]. 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 inclusion of energy storage is of extreme significance in facilitating the shift towards sustainable energy systems that mainly depend on renewable sources [26]. 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 [27]. This energy transformation requires energy systems of different levels to adapt to smart energy systems, which focus on merging the electricity, heating, and transport sectors, alongside various storage options, to create the necessary flexibility for integrating large penetrations of fluctuating renewable energy [28].

In the context of moving closer to a prosperous, modern, competitive net-zero greenhouse gas economy and reach Paris Agreement commitments the EU developed a strategic long-term vision for climate neutral economy which analyses different scenarios to achieve 80% to 100% decarbonization levels by 2050 [29]. The development pathways differ in level of electrification, utilization of hydrogen and power-to-X technologies (hydrogen, methane, other synthetic gases or liquids). It is estimated that for future energy systems that are highly dependent on RES, high penetration of storage capacities (at least six times larger than currently installed levels) is of primary importance to support the fluctuations of renewable energy.

Decentralization and role of municipalities

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 [30]. 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 [31]. 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 [31]. Municipalities are both consumers and energy planners, providers and advisors for their energy end-user groups [31], [32]. Municipalities own and operate regional energy facilities due to the dispersed nature of renewable energy generation and the decentralized structure of the energy sector. Improving energy efficiency and fostering renewable energy resource (RES) adaptation are local matters, and local authorities should provide the right conditions for it, considering the region’s specifics, such as geographical conditions and spatial planning.

The strategic planning and development of municipal energy infrastructure involve multiple stakeholders, including energy producers, suppliers, transmission system operators, regulatory agencies, environmental advocacy organisations, residents of the municipal territory, and other relevant parties. Each individual has their own distinct mental models, comprehension, and perspectives. In order to facilitate successful collaborative governance [33] and the execution of the most optimal solution, it is essential to comprehend the needs and priorities of each stakeholder group involved.

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, with these emissions largely driven by fossil fuel combustion (Fig. 1.1). While the EU-27 achieved a 13% reduction in total GHG emissions over a 10-year period from 2013 to 2022, Latvia's progress was more modest, with a 7% decrease during the period [34].

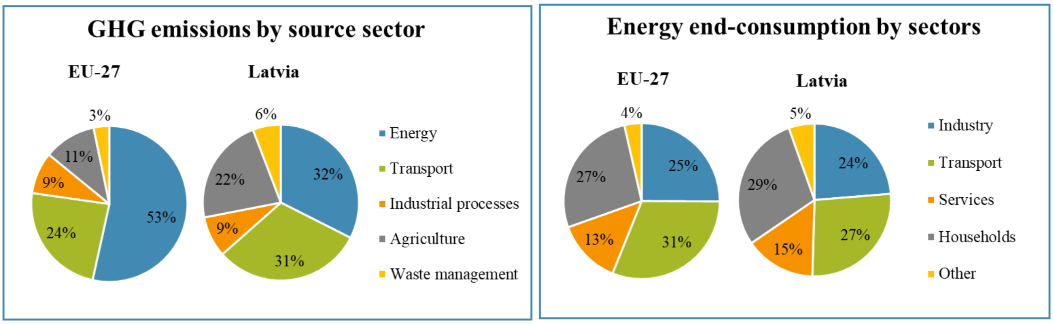


Fig. 1.1. Distribution of GHG emissions (excluding LULUCF) and energy consumption by sectors in the EU and Latvia in 2022 [34], [35].

Total energy consumption in EU-27 decreased by 3% while increased by 2% in Latvia over a 10-year period from 2013 to 2022. 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, accounting for one fourth of total energy consumption [35].

Industry, and in particular carbon- and energy-intensive manufacturing, will play a crucial role in meeting global climate change targets. While EU industrial energy use fell by 15% from 2005 to 2017, some countries, including Latvia (7%), recorded a significant increase in the industry energy end use [36]. The overall energy efficiency of the industry strongly depends on energy utilization practices of all the industrial sub-sectors combined [37].

The transport sector is one of the largest polluters globally and in the EU. Unlike other major sectors in the EU, its GHG emissions have risen significantly. As a result, the transport sector's growth, which requires higher energy demand and drives up GHG emissions, is currently occurring at the expense of realized energy efficiency efforts by other sectors that have succeeded in gradually reducing their energy and emissions intensities [38]. The transport sector heavily relies on fossil fuels, which are carbon-intensive and largely imported. To reduce import dependency and meet climate neutrality goals by 2050, the EU aims to cut transport GHG emissions by at least 90% from 1990 levels [39].

In the EU-27, renewable energy accounted for 38% of total electricity production in 2022, with wind (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%. Nuclear energy provided 22% of the total gross electricity production. Despite the growth of renewables, fossil fuels continued to dominate, with natural gas and other fossil fuels (coal, oil shale, oil, and petroleum products) accounting for 20% of total electricity production [34].

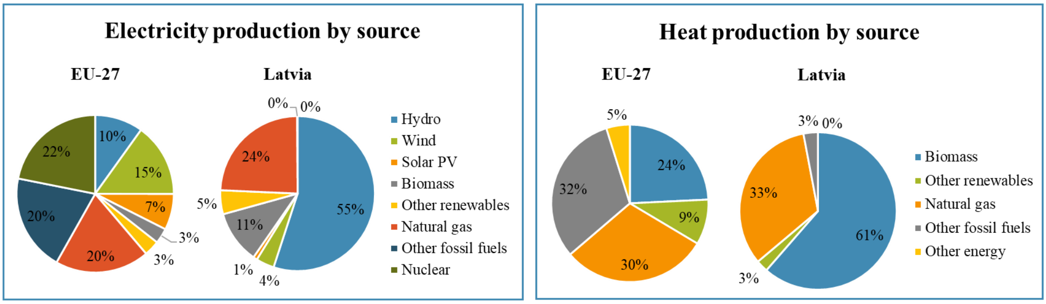


Fig. 1.2. Gross electricity and heat production by source in the EU and Latvia in 2022 [35].

In 2022, Latvia's electricity production was dominated by hydro energy (55%), with biomass (11%), wind and solar PV (5%), and other renewables like biogas (5%). Natural gas contributed nearly 24%, bringing the total share of RES to 76% [35]. 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, such as coal, oil and petroleum products, and oil shale, making up 32%. Biomass played a significant role, contributing 24%, while other renewables, including geothermal and solar thermal, accounted for 9% [35]. 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 [35].

2. METHODOLOGY

The methodological framework of this Thesis comprises three main approaches. First, the composite index method was used to study the initial sustainability level of the studied sector or research problem. Second, decomposition analysis was used to study the historical progress of decarbonization and sustainability over time. Third, a fuzzy cognitive mapping approach was used to account for social factors and their importance in investigating energy and climate policy.

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, (4) indicator weight assessment, (5) indicator aggregation, and (6) benchmarking, as illustrated in Fig. 2.1.

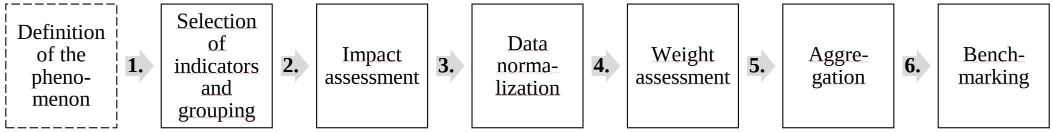


Fig. 2.1. Key steps for the construction of the composite index.

At first, indicators were selected based on academic research and data availability. Both quantitative and mixed approach were used for data collection of selected indicators. Quantitative approach included data collection from academic literature, databases and assessment reports. While mixed approach used a combination of quantitative and qualitative approach. Qualitative approach included data collection from scientific literature, expert interviews or research observations where numerical values were further obtained through the predefined qualitative assessment scales. After indicator data selection, if possible, indicators were grouped into predefined dimensions. Further indicators were assessed according to their positive or negative impact on overall. If an increasing value of the indicator leads to higher sustainability, the indicator was classified as a positive impact indicator. On the other hand, if a growing value for the indicator leads to lower sustainability, the indicator was classified as a negative impact indicator. To make the units of measurement of the different indicators comparable, the collected data were further normalized using Eq. (2.1) – Eq. (2.2).

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

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

where

I_N^+ – a normalized indicator of a positive impact;

I_N^- – a normalized indicator of a negative impact;

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

I_{max} – the maximum value of an indicator;

I_{min} – the minimum value of an indicator.

After normalizing the data, impact weights were assigned for both indicators and dimensions. There are two weighting techniques used throughout the research – equal weighting and expert weighting. The final calculation step is the aggregation of the obtained normalized and weighted indicators. First, indicators are aggregated in the corresponding dimensions using the Eq. (2.3).

$$I_D = \sum w \times I_N^{+} + \sum w \times I_N^{-} , \tag{2.3}$$

where

I_D – the sub-index of a particular dimension;

w – the value of determined weight of an indicator;

I_N^{+} and I_N^{-} – normalized indicators in each dimension.

If the developed composite index did not have predefined dimensions, then this step represents the final composite index calculation step, excluding further dimension aggregation. If it had predefined dimensions, then the final composite index construction is determined by the accumulated sum for each of the dimensions with its corresponding weight. The calculation is done according to Eq. (2.4).

$$CI = \sum w \times I_D , \tag{2.4}$$

where

CI – the final composite index;

w – the value of determined weight of a dimension.

Once the composite index results were obtained, then the benchmarking approach was used to evaluate different levels of sustainability. Benchmarks were calculated as weighted average values of composite indices obtained for subjects under the study.

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	Economic, technical, environmental	12	Quantitative	Equal
Transport	Transport composite sustainability index	2017	Cross-country	Mobility, sustainability, innovation, environmental	15	Quantitative	Equal
National energy	Energy sustainability index	2019	Cross-country	No dimensions	6	Quantitative	Equal
Municipal energy	Municipal energy transition index	2022	Cross-municipal	Energy efficiency, decarbonization, smart energy	9	Mixed	Equal
Energy storage	PESTLE composite index	2023	Cross-technology	Political, economic, social, technological, legal, environmental	19	Mixed	Expert
Policy	Policy risk index	2021	Cross-case	Political, technical, economic, environmental, social, administrative	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 outlined in Table 2.2.

Table 2.2

Classification of Selected Indicators and Data Sources for Industrial EEI Construction

Dimension	**Indicator**	**Variable**	**Impact**	**Data source**
Economic	Value added per energy use	Value added at factor cost/Net domestic energy use	+	[40], [41]
	Generated turnover per energy use	Turnover/Net domestic energy use	+	[40], [41]
	Energy costs	Purchases of energy products/Turnover	-	[42], [40]
	Energy taxes per generated turnover	Energy taxes/Turnover	-	[43], [40]
Technical	Investment per energy use	Gross investment in existing buildings, structures, machinery and equipment, construction and alteration of buildings/Net domestic energy use	+	[40], [41]
	Share of ISO 50001 registered companies	Number of ISO 50001 registered companies/Total number of companies	+	[44], [40]
	Share of large size companies	Number of enterprises with 250 persons employed or more/Total number of enterprises	+	[45]
	Energy use per employee	Net domestic energy use/Number of employees	-	[41], [40]
Environ-mental	Greenhouse gas intensity	Greenhouse gases in tons/Value added at factor cost	-	[46], [40]
	Use of fossil energy resources	Fossil energy products/Total energy products	-	[47]
	Environment protection activity	Percentage of companies that eliminated energy consumption or CO_2 emissions by innovation activities within the organization	+	[48]
	CO_2 productivity	Generated turnover/Tons of CO_2 emissions	+	[40], [46]

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 obtained from Eurostat, European Commission, and Odysee-Mure databases. The selected indicators of transport sustainability index were summarized in Table 2.3.

A cross-country comparison of transport sustainability levels is an effective tool for identifying similarities and differences between different countries and classifying which countries can be considered pioneers in transport sustainability and which lag behind. The index was further used to set the benchmarks and quickly identify the bottlenecks that national governments should emphasize to accelerate the implementation of more sustainable practices in the transport sector.

Table 2.3

Selected Indicators, Data Sources and Impact Evaluation for Transport Sustainability Index

Dimension	**Indicator**	**Description of the indicator**	**Impact**	**Data source**
Mobility	Passenger cars per 1000 inhabitants	A specific indicator that determines the number of passenger cars per 1000 inhabitants in the country	-	[49]
	Passenger cars per GDP	A specific indicator measuring the ratio of passenger cars per national GDP	-	[50], [51]
	Share of public transport in total land passenger traffic	A specific indicator that determines the share of public transport (bus, train, tram, and metro) in the total domestic passenger-kilometers traveled	+	[52]
	Annual distance traveled in public transport per capita	A specific indicator measuring the yearly distance traveled per capita in public transport (buses, trains, trams, and metros)	+	[52]
Sustainability	Quality of roads	The road quality assessment for each country is based on the World Economic Forum survey included in the Global Competitiveness Assessment	+	[53]
	Hours spent in road congestion annually	Represent hours spent by the average driver in road congestion each year. The figure accounts for two 30 km trips per day (morning and evening maximum) and 220 working days. It considers all major roads in the Member States for which data are available (approximately 2 500 000 kilometers)	-	[53]
	Transposition of EU transport directives	Percentage of EU transport-related directives where the measures taken to improve the transport sector according to EU requirements were notified to the European Commission at the end of the respective year	+	[53]
	Consumer satisfaction with urban transport	The assessment is based on the market performance indicator, a composite index that measures the performance according to the consumers' opinions. The data is retrieved from DG JUST Summary of consumer market results.	+	[53]
Innovation	Market share of electric passenger cars	A percentage of newly registered electric vehicles in the given year, including battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV)	+	[54]
	Electric vehicle charging points per 1000 inhabitants	A number of electric vehicle charging points per 100,000 urban residents (persons living in "urban areas" based on DEGURBA classification of urban/rural areas).	+	[54]
	Share of alternative fuel vehicles in the total stock of cars	The percentage of alternative fuel vehicles in the total number of vehicles. Include electric vehicles, plug-in hybrid vehicles (PHEVs), and compressed natural gas (CNG) vehicles.	+	[52]
Environmental	Share of biofuel in transport energy consumption	An indicator measuring the proportion of biofuels in total transport energy balance.	+	[52]
	Emissions from the transport sector per number of inhabitants	A specific indicator measuring greenhouse gas emissions in relation to the total population of a country.	-	[46], [55]
	Average CO_2 emissions per km from new passenger cars	An indicator measuring the average CO_2 emissions of new passenger cars per kilometer driven.	-	[56]
	Share of high emission cars in total sales	An indicator measuring the percentage of total vehicle sales that are high GHG emitting cars (specific emissions per kilometer between 115 and 130 gCO_2/km).	-	[52]

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 goal of the ESCI was to characterize the existing situation of energy sustainability in each country. 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. Table 2.4. summarizes the selected indicators of the energy sustainability composite index. Data were taken from publicly available databases - Eurostat and Odysee Mure. Data was selected for 2019 as this was the latest available data for all selected indicators for all EU-27 countries.

Table 2.4

Selected Indicators of Energy Sustainability Composite Index (ESCI)

Indicator	**Description**	**Impact**	**Data source**
Energy import dependency	Net energy imports divided by the gross available energy, %	-	[57]
Share of renewable energy sources	Share of renewable energy in gross final energy consumption, %	+	[24]
Primary energy intensity	Primary energy intensity at purchasing power parities (ppp) with climatic corrections, koe/EUR2015p	-	[58]
Energy efficiency	Total energy consumption per number of inhabitants, Mtoe/population	-	[59], [60]
CO_2 emission intensity	Total CO_2 emissions from fuel combustion activities per total final energy consumption (with climatic corrections), $MtCO_2$/Mtoe	-	[61], [59]
Energy poverty	Share of population unable to keep home adequately warm, %	-	[62]

Municipal energy transition index

The municipal energy transition index (ETI) was constructed to assess the extent to which municipal efforts have been successful in the adaptation of low-carbon energy systems, and what is the current state of municipal initiatives concerning regional energy transitions. ETI incorporated nine indicators grouped into three main dimensions of sustainable municipal energy transition: energy efficiency, energy decarbonization, and smart energy system deployment, as outlined in Table 2.5. 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).

There were two main approaches in data collection for selected indicators – quantitative and qualitative assessment approaches. For quantitative indicators $i_1 – i_6$ actual municipal data was used for the year 2022. However, due to data limitations, an evaluation scale was introduced for the indicators i_5 and i_6. RES heat share indicator (i_5) includes both the renewable energy in district heating and local heating supply of municipal buildings. Data limitations occurred in certain missing specific fuel consumption figures, where minor approximations had to be made. Similarly, an evaluation scale was introduced for the transport decarbonization indicator (i_6). This includes fuel consumption in private and public municipal transport. Approximations were made on the specific fuel consumption and concrete distances travelled. However, sensitivity analysis revealed that the evaluation scale does not significantly impact the overall outcome or results of the composite index. Moreover, for qualitative indicators $i_7 – i_9$ an assessment approach using a five-point scale was introduced, with 5 points being the highest, and 1 the lowest assessment value. Qualitative indicators were assessed based on the information received from the municipal representatives through private one-to-one discussions and municipal energy data provided.

Table 2.5

Selected Composite Municipal Energy Transition Index Indicators and Values

Indicator	**Explanation**	**Unit of measure**	**Impact**	**Gulbene**	**Tukums**	**Taurage**	**Tomelilla**	**Wejherowo**
Energy efficiency dimension								
Public building renovation trend (i_1)	Proportion of municipal buildings renovated from total heating area of buildings	%	+	51.9	34	21.28	63	67
Infrastructure electricity consumption efficiency (i_2)	Municipal electricity consumption per inhabitants	kWh/inhabitant	-	167.4	147.5	100.6	206.4	172.3
Public building heat consumption efficiency (i_3)	Average heat consumption of municipal buildings	kWh/m^2	-	106.8	132.8	133.6	126.0	92.7
Energy decarbonization dimension								
RES power installation diffusion (i_4)	Installed municipal RES power plants per inhabitants	MW/inhabitant	+	0.47	0.21	1.50	2.60	0
RES heat share (i_5)	Share of produced heat energy from renewable energy resources	Evaluation scale: 5p: 95% -100% 4p: 85%-95% 3p: 50% – 84% 2p: 10% - 49% 1p: 1% - 9%	+	95% - 100% (5)	85%-95% (4)	85%-95% (4)	95% - 100% (5)	1% - 9% (1)
Transport decarbonization (i_6)	Share of electrical and alternative fuel transportation in municipal transport system	Evaluation scale: 5p: 40% - 100% 4p: 30% - 39% 3p: 20% - 29% 2p: 10% - 19% 1p: 1% - 9%	+	1% - 9% (1)	1% - 9% (1)	10% - 19% (2)	20% - 29% (4)	10% - 19% (2)
Smart energy system dimension								
Digitalization and energy monitoring data accessibility (i_7)	Level of data quality and complexity of energy data collection	5-point scale, with 5-the highest, 1- the lowest	+	4	3	3	2	3
Energy storage deployment (i_8)	Existing RES storage technologies installed	5-point scale, with 5-the highest, 1- the lowest	+	2	1	1	1	1
Innovation acceptance level (i_9)	Considerations of innovation adaptation such as hydrogen, and its derivatives	5-point scale, with 5-the highest, 1- the lowest	+	2	2	2	3	4

Energy storage PESTLE composite index

The PESLTE analysis is a framework used to evaluate multidimensional factors affecting complex systems, specific industries, organizations, or products. Each letter of PESTLE framework encrypts the first letter of the factor included in the analysis – P-political, E-economic, S-social, T-technological, L-legal, E-environmental [63], [64]. This research applied the PESTLE framework to select and analyze relevant factors that influence the deployment of different renewable energy storage technologies in a municipal context. To compare technologies based on the PESTLE analysis indicators (see Table 2.6), the composite index method was applied to quantify and measure the influencing factors for each technology. The developed model was approbated in a case study in Gulbene municipality where four different alternative energy storage technologies used for excess variable RES accumulation 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).

Table 2.6

Selected Energy Storage PESTLE Composite Index Indicators and Values

Indicator	**Unit**	**Data source**	**Impact**	**Batteries**	**Thermal**	**Hydrogen**	**Biomethane**
Political							
State political initiative and support	Scale from 1-very low to 5-very high	Survey	+	2.8	2.6	1.8	1.8
Municipal priorities and necessity	Scale from 1-very low to 5-very high	Survey	+	3.2	4.2	2.2	1.8
National and international level policy targets	Scale from 1-very low to 5-very high	[65], [66]	+	3	3	2	1
Economic							
CAPEX	EUR/kW	[67]	-	725	309	3500	2400
OPEX	EUR/MWh	[68]	-	2	1.8	30	50
Capital availability for municipal co-financing	Scale from 1-very low to 5-very high	Survey	+	2.6	2.8	1.6	1.8
Social							
Public attitude and knowledge	Scale from 1-very negative to 5-very positive	Survey	+	3.2	3.4	2.2	2.2
Knowledge of the municipality about technology	Scale from 1-very low to 5-very high	Survey	+	3.4	3	2	2
Technological							
Technology level of maturity	Scale from 1- not mature to 5-very mature	[69], [70], [71]	+	4	4	2	2.5
Round-trip efficiency	%	[67], [72]	+	87	77	30	53.5
Response time	time (1-very slow, 5-very fast])	[67]	+	ms (5)	30 sec. - 3 min. (3.5)	< sec - < min (4)	sec (4.5)
Storage duration at full power	time (1-very low, 5-very high)	[67]	+	min-hours (2)	hours-months (4)	hours – weeks (3)	some weeks (4)
Level of complexity for technology to be integrated in the existing grid	Scale from 1-very low to 5-very high	Survey	-	3	3.2	4.2	4
Legal							
Level of complexity to get environmental permit	Scale from 1-very complicated to 5-very easy	Survey	+	3.6	3.8	3	2.8
Level of bureaucratic burden to get municipal approval	Scale from 1-very low to 5-very high	Survey	-	1.8	2.2	2.8	3
Environmental							
Potential environmental risk	Scale from 1-no risk to 5-high risk	[73], [74], [71], [75]	-	3	2	3	3
Lifetime of technology	Years	[67]	+	15	30	18	30
Environmental impact	gCO_{2e}/kWh	[73], [74], [71], [75]	-	84	15	0	20
Territorial availability for technology installation without impacting environment	Scale from 1-very low availability to 5-very high availability	Survey	+	4.4	4.4	2.2	2.2

Data collection on selected indicators was organized in two levels. First level included data collection on thechnology performance and sustainability parameters. Data were collected from scientific literature [73], [74], [75], [76], [77] and technology databases such as the European Commission's Energy Storage Database [67], the Danish Energy Agency's Outlook on Energy Storage Technologies [68], technology reports from IRENA [69], [70], technology reports from the European Association for Storage of Energy [71], and other technology outlooks [65]. For several indicators such as CAPEX, OPEX, round-trip efficiency, and environmental impact, the data found in the literature and technology datasets included a value that had a data range. In this study, the mean values of the specified data range were used. In the context of thermal energy, the term "round-trip efficiency" refers to efficiency. For the qualitative indicators, assessment scale was used to quantify the indicators comparing the different technologies. The assessment scale was specified and defined for each qualitative indicator as shown in Table 2.6. The second level included data collection from surveys and interviews with municipality representatives. The questionnaire asked respondents to evaluate the impact of all six PESTLE factors where the average results were further used in the weight assessment of indicators during the construction of composite index.

Expert weights were used to calculate the PESTLE composite index. The values of the weights for each dimension of PESTLE were obtained from the surveys with municipality representatives. The average values were used as weights for each dimension of PESTLE in constructing the composite index - 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

The policy risk index was constructed to obtain a comprehensive, in-depth risk assessment of climate and energy policies. The methodology of this research was constructed based on previous studies describing a range of risk factors affecting the success or failure of energy policy and techniques for measuring them. 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 - political, technical, economic, environmental, social and administrative. Table 2.7. summarizes selected policy risk indicators and dimensions.

The risk matrix framework was applied for the evaluation of identified risk indicators. 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 [78]. The level of each component is assessed according to a five-point scale as outlined in Table 2.8 Therefore, two grades were assigned for each risk indicator – one for the risk likelihood and another for the risk consequence.

Political risk category reflects the dysfunctionality of the existing legal system and regulatory risks that hinder the development of renewable energy and climate change mitigation programs. Technical risk category incorporates risks related to the availability of technical and human capital and productivity. The economic risk category includes financial and market risks that affect the economic stability and profitability of the operations or investment projects carried out. Environmental risk category consists of risk indicators that measure the impact on the environment that results from the implementation of policies or projects. Social risk category refers to social issues related to public acceptance of the project or policy. Administrative risk category includes risks related to the sufficient provision of support services and information.

Table 2.7

Selected Policy Risk Index Indicators and Risk Classification

Risk category	Risk indicator	Risk description	Reference
Political	Legal	Sudden changes in the policy and support schemes	[79], [80], [81], [82], [83]
	Regulatory	No clear guidelines, vision, conditions and requirements of the implemented legislation and regulatory	[80], [83], [84], [85], [86]
	Incentives	Lack of government incentives and limited promotion of the policy	[80], [85], [86]
	Long-term	Limited long-term planning and objectives of the policy (overlooking important details for legislation)	[80], [87], [88]
Technical	Infrastructure	Limited access to technology and infrastructure	[79], [80], [81], [83], [84], [85], [86]
	Operation	Limited technical capacity	[83], [84], [85], [86], [89]
	Maintenance	Unreliability of technologies	[80], [81], [82], [85], [86], [89], [90]
	Productivity	Lack of employee knowledge, experience and training	[80], [81], [83], [85], [86], [90], [91]
Economic	Aid	Lack of subsidies and support mechanisms to stimulate the implementation of the policy	[80], [83], [84], [85], [86], [88], [92], [93]
	Policy	Inefficient fiscal and other policy instruments (taxation regime for the tariff determination, feed-in tariffs, quota obligation scheme, etc.)	[81], [83], [85], [90], [92]
	Financial	Limited financing opportunities (insufficient access to investment and operating capital)	[80], [81], [82], [83], [85], [86], [90], [92]
	Market	Inefficient production and operation costs (OPEX), high capital and investment costs (CAPEX), small market size, limited opportunities for economies of scale	[80], [81], [82], [83], [84], [85], [86], [92]
Environmental	Environment	Risk of environmental damage and creation of direct negative effect on the environment	[79], [80], [81], [85], [89], [94]
	Emissions	Risk of not achieving the reduction of carbon footprint	[80], [81]
	Life cycle	Insufficient provision and assessment project/program life cycle (centralized vs decentralized, regional vs global, urban vs rural)	[80], [81]
	Resources	Risk of creating indirect environmental damage (e.g. stimulates the consumption of additional resources such as energy, materials, labor, and others) or unknown environment risks	[80], [85]
Social	Acceptance	Limited public acceptance	[79], [80], [81], [83], [85], [94]
	Adaptability	Public comfort with the existing situation and unwillingness to change	[83], [85], [93]
	Knowledge	Lack of public knowledge	[80], [83], [86]
	Labor	Lack of available labor force that limits the capacity for adequate implementation of the project	[81], [85]
Administrative	Communication	Inadequate and insufficient information dissemination	[81], [85]
	Project management	Dysfunctional project administration, management and program/project monitoring	[90], [95]
	Bureaucracy	High bureaucracy and complex approval/administration process	[79], [80], [81], [83]
	Institutions	Lack of administrative institutions, support service, professional research institutions	[83], [85], [86], [88]

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 according to the composite index calculation methodology as described in the beginning of this section.

$$R_i = R_{likelihood} \times R_{consequence}, \tag{2.5}$$

where

R_i – a risk score;

$R_{likelihood}$ – the obtained score of a risk likelihood;

$R_{consequence}$ – the obtained score of a risk consequence.

Table 2.8

Evaluation Scales for the Policy Risk Indicator Assessment

Score	**Likelihood (*p* - probability)**	**Consequence**
5	Almost certain (95% - 100%)	Catastrophic
4	Likely (70% - <95%)	Major
3	Possible (30% - <70%)	Moderate
2	Unlikely (5% - <30%)	Minor
1	Rare (0% - <5%)	Negligible

The method was applied to assess five different climate policy instruments, using both an ex-post and ex-ante assessment (Table 2.9). Five energy sector experts reviewed case studies, completed risk assessments, and rated policy risks on a five-point scale. The summarized assessments yielded policy risk index scores based on average expert ratings.

Table 2.9

Selected Policy Instruments for Policy Risk Index Case Study Evaluation

	Name of the instrument	Type of instrument	Type of evaluation
Case 1	Construction of wind energy park	Project	Ex-ante
Case 2	Energy efficiency monitoring system program	Program	Ex-post
Case 3	The climate financial instrument (CCFI)	Program	Ex-post
Case 4	Development of distributed energy generation	Policy	Ex-ante
Case 5	Development of centralized energy generation	Policy	Ex-ante

2.2. Decomposition analysis

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 2.10. summarizes the LMDI decomposition analyses developed.

Table 2.10

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
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 [96].

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

where
Y – the indicator being measured;
X_n – 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
$\Delta\, Y_{Xn}$ – the effect on *Y* from changes in driver X_n .

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

$$\Delta\, Y_{Xn} = \sum_i \frac{Y^T - Y^0}{lnY - lnY^0} ln \frac{X_{n_1}^{\,T}}{X_{n_1}^{\,0}} \, , \tag{2.8}$$

where
Y^T – the value of an indicator in future year T;
Y^0 – the value 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 manufacturing industry were determined as a sum of energy-related CO_2 emissions of each industrial sub-sector. The manufacturing sub-sectors were selected according to the classification nomenclature NACE Rev. 2 and grouped according to the statistical subdivision of the industrial sector [97]. Energy-related CO_2 emissions in industry were decomposed according to Eq. (2.9). LMDI decomposition analysis indicators for industrial energy-related CO_2 emissions are summarized in Table 2.11.

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

where
C – total aggregated energy-related CO_2 emissions;
Q – total produced volumes expressed as total value-added;
E – total energy consumption;
S_i – an industrial production activity;
I_i – energy intensity;
F_{ij} – fuel mix;
M_{ij} – 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, e.g. natural gas, electricity, biofuels and others. The further decomposition construction and calculation was performed based on Eqs. (2.7) and (2.8).

Table 2.11

LMDI Decomposition Analysis Indicators for Industrial Energy-Related CO_2 Emissions

Indicator	Time period	Variable	Explanation	Data source
Activity effect	1995-2019	Aggregated industrial value added ($\sum_i EUR_i$)*	Measures changes in the growth of total production output	[42], [51]
Structural effect	1995-2019	Share of production output of a subsector in the total industrial production ($EUR_i/\sum_i EUR_i$)*	Measures the level of restructuring in industry by shifting to less energy-intensive sectors	[42], [51]
Energy intensity effect	1995-2019	The amount of energy consumed per unit of production output (GWh_i/EUR_i)*	Measures the level of energy efficiency improvement	[51], [36]
Fuel mix effect	1995-2019	Share of energy consumption of non-renewable energy products ($E_{ij}/\sum_i E_i$)	Measures the decarbonization effect of the industry	[36]
Emission intensity effect	1995-2019	Emission intensity of consumed energy resources (tCO_2/GWh)*	Measures the emissions intensity of the fuel mix	[36]

*chain-linked volumes of base year 2015.

Data utilized in this study was collected from Eurostat and Central Statistical Bureau of Latvia (CSB) databases [42], [51]. Data on emission factors for utilized fuels were taken from IPCC guidelines for national greenhouse gas inventories on default emission factors for stationary combustion in manufacturing industries and construction [98]. The data for CO_2 emission factor for electricity produced in Latvia were collected from European Environment Agency [99]. The CO_2 emission factor for heat produced in heat plants and combined heat and power plants in Latvia was calculated according to the approach of Cabinet Regulation No. 42. of the Republic of Latvia “Methodology for Calculating Greenhouse Gas Emissions” [100].

Transport sector

LMDI decomposition analysis additive approach was applied to measure changes in aggregate GHG emissions of transport sector determined by emission intensity effect, RES transition effect, energy intensity effect, economic growth effect, and population growth effect. Table 2.12 summarizes the indicators of transport LMDI decomposition analysis. GHG emissions from fuel combustion in transport in 28 European countries were decomposed using Eq. (2.10) based on [101], [102].

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

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 of this study. All the data was collected from the Eurostat database [34], [103], [51], [60].

Table 2.12

Description of Decomposition Analysis Indicators of Transport Sector

Factor	**Notation**	**Indicator**	**Description**
Emission intensity effect	*Em*	Total GHG emission in thousand tons of CO_2 equivalents from fuel combustion in transport per total consumption of fossil fuels in the transport sector (GHG_i/FFC_i)	Measures changes in total fossil fuel emissions intensity in the transport sector. Changes in this indicator could indicate changes in modal shift (e.g., higher utilization of public transportation) and transition to less emission-intensive fossil fuels (e.g., shift from diesel oil to LPG, etc.).
RES transition effect	*Res*	Share of fossil fuel consumption in total energy consumption in the transport sector (FFC_i/TEC_i)	Measures the RES transition and the impact of decarbonization on the overall energy mix of the transport sector (reducing the share of fossil fuels and increasing the share of biofuels and electricity in the overall energy balance of the transport sector).
Energy intensity effect	*En*	Total energy consumption of the transport sector per unit of produced gross domestic product (TEC_i/GDP_i)	Measures changes in energy efficiency in the transport sector and shows the energy savings achieved through technical improvements (manufacturing cars with lower specific fuel consumption, more efficient engines, etc.).
Economic growth effect	*Gdp*	Total gross domestic product per capita (GDP_i/POP_i)	Measures changes in economic growth and its impact on higher demand for transportation services (e.g., with higher income, more households can afford to purchase a car, etc.).
Population growth effect	*Pop*	Total population on 1 January (POP_i)	Measures changes in total population. Population growth requires increased energy consumption by the transportation sector due to increased transportation demand.

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 [104].

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

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.

Table 2.13. summarizes energy sector LMDI decomposition analysis impact factors. The further decomposition construction and calculation were performed based on Eqs. (2.7) and (2.8).

Table 2.13

LMDI Decomposition Analysis Impact Factors of National Energy Sector

Factor	Expression	Data source
Δ Emission intensity	Total CO_2 emissions from fuel combustion/ Total inland energy consumption	[61], [51]
Δ Energy intensity	Total inland energy consumption/ GDP (2015 chain linked volumes)	[35], [51]
Δ GDP growth	GDP (2015 chain linked volumes)/ Total Population	[51], [60]
Δ Population growth	Total population	[60]

Renewable electricity generation

The LMDI was used to decompose the changes in production values of gross electricity from RES 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. Eq. (2.12) demonstrates the identity between the LMDI factors that determine the changes in the total amount of energy produced by RES, adapted from [105] and [106]. Moreover, this study extends the LMDI decomposition analysis to examine how wind and solar PV installations, which have experienced significant growth in the past decade, contribute to the overall increase in renewable energy sources. Eqs. (2.13) and (2.14) are used to examine in more detail the changes in electricity generation from wind and solar PV.

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

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

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

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, 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 construction and calculation was performed based on Eqs. (2.7) and (2.8). Table 2.14. summarizes LMDI decomposition analysis decomposers used to decompose the changes in production values of gross electricity from RES, wind, and solar PV over a ten-year period. All data used for LMDI decomposition analysis construction were retrieved from Eurostat [35], [51], [107], [60], [108]. All values of the selected variables were collected for all 27 EU countries. The data series covered the period from 2012 to 2021, i.e. the most recent data available at the time this study was conducted.

Table 2.14

Description of LMDI Decomposition Analysis Decomposers for Generated Electricity from RES

Notation	**Factor**	**Unit**	**Factor calculation**
RSH	RES share effect	%	Gross electricity production from renewables (GWh)/ Total gross electricity production (GWh)
EI	Energy intensity effect	GWh/MEUR	Total gross electricity production (GWh)/ Gross domestic product (MEUR)
RPR	RES capacity productivity effect	MEUR/MW	Gross domestic product (MEUR)/Electricity production capacities for renewables (MW)
RD	RES deployment per capita effect	MW/population	Electricity production capacities for renewables (MW)/Population (number)
WSH	Wind share effect	%	Gross electricity production from wind (GWh)/Gross electricity production from renewables (GWh)
WPR	Wind capacity productivity effect	MEUR/MW	Gross domestic product (MEUR)/Electricity production capacities for wind (MW)
WD	Wind deployment per capita effect	MW/population	Electricity production capacities for wind (MW)/Population (number)
PVSH	Solar PV share effect	%	Gross electricity production from solar PV (GWh)/Gross electricity production from renewables (GWh)
PVPR	Solar PV capacity productivity effect	MEUR/MW	Gross domestic product (MEUR)/Electricity production capacities for solar PV (MW)
PVD	Solar PV deployment per capita effect	MW/population	Electricity production capacities for solar PV (MW)/Population (number)

Energy independence

The LMDI decomposition analysis method was used to study changes in net energy imports of EU countries. According to LMDI, 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. Table 2.15 summarizes all the factors used in the decomposition analysis.

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

where

NI – net energy imports;

EN – gross available energy;

GDP – gross domestic product;

POP – population;

DEP – energy import dependency;

EE – energy efficiency;

EC – economic growth;

i – a particular country.

Table 2.15

Description of the LMDI Decomposition Analysis Factors for Net Energy Imports

Factor	Indicator	Description
Energy dependency effect (*DEP*)	Net imports (imports-exports) per gross available energy (NI_i/EN_i)	Measures changes in energy import dependency and reliance on energy resources abroad. Positive value shows greater energy import dependency and negative value shows reduced energy import dependency.
Energy efficiency effect (*EE*)	Gross available energy per gross domestic product (EN_i/GDP_i)	Measures improvements in energy efficiency by reduced energy intensity of economy. Positive value shows negative trend and decrease in energy efficiency, negative value shows significant improvements in energy efficiency by more efficient use of energy resources.
Economic growth effect (*EC*)	Total gross domestic product per number of inhabitants (GDP_i/POP_i)	Measures changes in economic growth and development which directly impact the amount of energy resources used in the economy. Positive value shows increase in economic growth and its impact on energy demand increase, negative value shows decrease in economic output which in turn decreases overall demand for energy.
Population growth effect (*POP*)	Total number of inhabitants (POP_i)	Measures changes in total number of inhabitants in a country. Positive value shows growth in population which pushed energy demand to increase, negative value shows decline in population which requires less energy resources to meet the needs of inhabitants.

Further decomposition construction and calculation was performed based on Eqs. (2.7) and (2.8). All the data used for this study is collected from the Eurostat database. Data was collected for all 27 EU member states for the period from 1995 to 2020 which was the latest available year for all the selected LMDI indicators [35], [51], [60], [109], [110].

Kaya identity

The LMDI decomposition method was used to examine the main drivers of change in overall GHG emissions in the economy. The analysis is conducted for a 10-year period from 2010 to 2019 for the EU-28 countries (including the UK). Kaya identity is a mathematical identity used to explain changes in total emissions by determining four main factors-emission intensity, energy intensity, economic growth, and population growth-according to Eq. (2.16), as retrieved from [104]. The advantage of the Kaya identity method is that it allows for the quantification of total CO_2 emissions by accounting for important determinants of emission changes. This technique is extensively employed to consider both energy and economic factors [111].

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

where
GHG – greenhouse gas emissions in certain period;
En – energy consumption in period;
GDP – gross domestic product in the period;
POP – 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). Data for Kaya identity decomposition was collected from Eurostat as summarized in Table 2.16.

Table 2.16

Data Sources for Kaya Identity Decomposition Analysis

Notation	Data	Data source
GHG_t	GHG emissions in tCO_2 eq (Total emissions as reported to international conventions (UNFCCC and CLRTAP))	[46]
En_t	Gross inland energy consumption in toe	[35]
GDP_t	GDP in MEUR (chain-linked volumes, base year 2015)	[51]
Pop_t	Population on 1 January	[60]

This analysis additionally investigated how historical patterns in GHG emission changes can be used to project future trends in GHG emissions, therefore the model was further extended. The following steps for calculating GHG projections were based on techniques shown in studies by [112] and [113]. If it is assumed 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 Eqs. (2.17)-(2.20).

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

$$ENI^T = ENI^0 \cdot (1+\beta) \tag{2.18}$$

$$GDP^T = GDP^0 \cdot (1+\delta) \tag{2.19}$$

$$POP^T = POP^0 \cdot (1+\varepsilon) \tag{2.20}$$

Following the fundamental basis of Kaya identity as demonstrated in Eq. (2.16) and coping it with Eq. (2.17)-(2.20), forecasted GHG emissions were obtained using Eq. (2.21).

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

Further yields are obtained that are explained in a relationship demonstrated in Eqs. (2.22)-(2.23).

$$\Delta\, EMI = z \cdot (1+\alpha) \tag{2.22}$$

$$z = \frac{GHG^0 \cdot [(1+\alpha)\cdot(1+\beta)\cdot(1+\delta)\cdot(1+\varepsilon) -1]}{ln[(1+\alpha)\cdot(1+\beta)\cdot(1+\delta)\cdot(1+\varepsilon) -1]} \tag{2.23}$$

Same relationship holds true for other factors, as presented in Eqs. (2.24)-(2.26).

$$\Delta\, ENI = z \cdot (1+\beta) \tag{2.24}$$

$$\Delta\, GDP = z \cdot (1+\delta) \tag{2.25}$$

$$\Delta\, POP = z \cdot (1+\varepsilon) \tag{2.26}$$

To derive Eq. (2.27) that is used for GHG emissions forecasting, Eqs. (2.22)-(2.26) are further inserted into Eq. (2.16).

$$GHG^T = GHG^0 + z \cdot (1+\alpha) + z \cdot (1+\beta) + z \cdot (1+\delta) + z \cdot (1+\varepsilon) \tag{2.27}$$

Future values of GHG emissions can be projected using Eq. (2.21) or (2.24) if growth rates are defined for each factor (*EMI, ENI, GDP, POP*). CAGRs are determined using an exponential smoothing forecast based on historical years from 2010 to 2019. The forecast is carried out for a period from 2020 to 2030. The key assumptions of the scenario analysis are shown in Table 2.17.

Table 2.17

Description of Forecast Scenarios

Scenario	**Explanation**	**Values**
Existing measures	Baseline scenario if current trends in GHG emission factors continue at the same historical levelized growth rate	Base values
Additional measures	Green growth scenario if current climate change measures are supplemented with stronger instruments to achieve larger GHG emission cuts	Lower 95% confidence bound values
Business as usual	No-climate-policy scenario if economic growth measures are boosted without consideration of sustainability aspects	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. FCM allows for the investigation of the social factors influencing energy transition challenges, which are often overlooked in energy sustainability studies. The multi-level stakeholder cognitive mapping approach used in this study followed several research steps, as illustrated in Fig. 2.2.

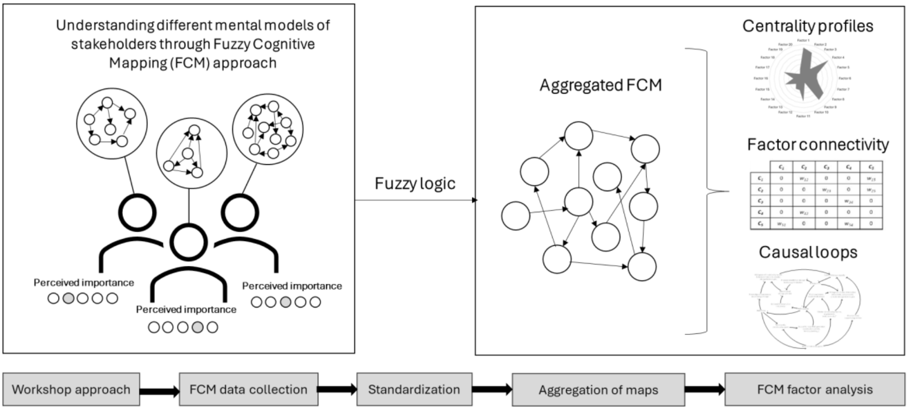


Fig. 2.2. Multi-level stakeholder cognitive mapping methodological approach, adapted from [114].

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. The individual mental models were then compiled, standardised and aggregated. When creating cognitive maps of stakeholders, there can be an unlimited number of knowledge sources with different degrees of knowledge and competence, all of which can be combined into one cognitive map. Stakeholder cognitive maps provide qualitative information; therefore, they are a convenient tool for predicting various models and representing changes in model behavior. The mapping approach can be used to model perceptions and social ideas regarding how the system works. Consolidated mental models of this research were analyzed in detail to determine the key impact factors for the deployment of energy storage in municipalities, the connectivity of the factors and the centrality profiles.

Two workshops were organized to collect FCM data and analyze the different perceptions of stakeholders. The stakeholders of the mental model workshops involved were from five main groups of expertise: research organizations, municipality representatives, energy clusters and consultancies, local infrastructure providers, and sectoral agencies. The aim of the workshops was to understand how target groups and energy experts perceive the barriers and opportunities for energy storage implementation in local energy systems. The participants link the factors in their mental models by determining their relationships. The factors included in the model can have a positive, negative, or no relationship. Fuzzy cognitive maps use fuzzy logic, meaning that the strengths between elements can be any real number in the range [-1,1].

The first workshop was held online and comprised a total of 19 participants. There were two groups of participants: first, energy experts working in the field of energy sector development, energy transition, and energy decarbonization; second, researchers working in a field not related to the energy sector. The second workshop was held on-site and comprised of 23 participants, who were grouped into groups of 2-3 participants. The participants were all local energy transition stakeholders representing different fields: municipal representatives, municipality energy service providers, energy clusters and associations, and sustainability research organizations. The participants were asked to work in groups and develop their mental models.

Map condensation and aggregation was used to better explain the structure of individual cognitive maps. The adjacency matrix for the simplified cognitive map was calculated by combining the effects of the elements within the categories according to Eq. (2.28).

$$C_i = \frac{\sum E_j}{n}, \tag{2.28}$$

where

C_i – weight for defined category;

E_j – weight for element within category;

n – summed number of elements.

An individual adjacency matrix of defined categories was used to obtain the combined cognitive map of the stakeholders. They are combined by applying Eq. (2.29) for each position in the matrix.

$$C_i^{sum} = \frac{\sum_1^m C_i}{m}, \tag{2.29}$$

where

C_i^{sum} is combined weight of category,

m is number of 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

The composite index method was used to study different aspects of energy efficiency in the industrial sector and to compare the efficiencies of different manufacturing subsectors in Latvia. Then, the LMDI decomposition analysis results are presented, which include an in-depth analysis of the green transformation trends in the industry.

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. EEI has been determined for the year 2017 based on the latest publicly available data at the time of the study. In total twelve indicators were considered and grouped into 3 separate sub-dimensions - economic, technical, and environmental. Each sub-dimension consisted of 4 explanatory indicators and then the three sub-dimensions were aggregated into the EEI. The results of the composite index should be interpreted in the following way – the higher the value of the index, the greater the sector’s improvement towards energy efficiency. The same applies for the values of dimension sub-indices.

Table 3.1. lists sub-indices of each dimension for all the sectors of the Latvian manufacturing industry. Overall, all sectors indicate weak energy efficiency with an industry average EEI score of 0.39. Environmental dimension sub-index with an average score of 0.48 has the most significant contribution on the overall EEI value. 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.

Table 3.1

The Results Obtained for Economic, Technical and Environmental Dimensions and EEI

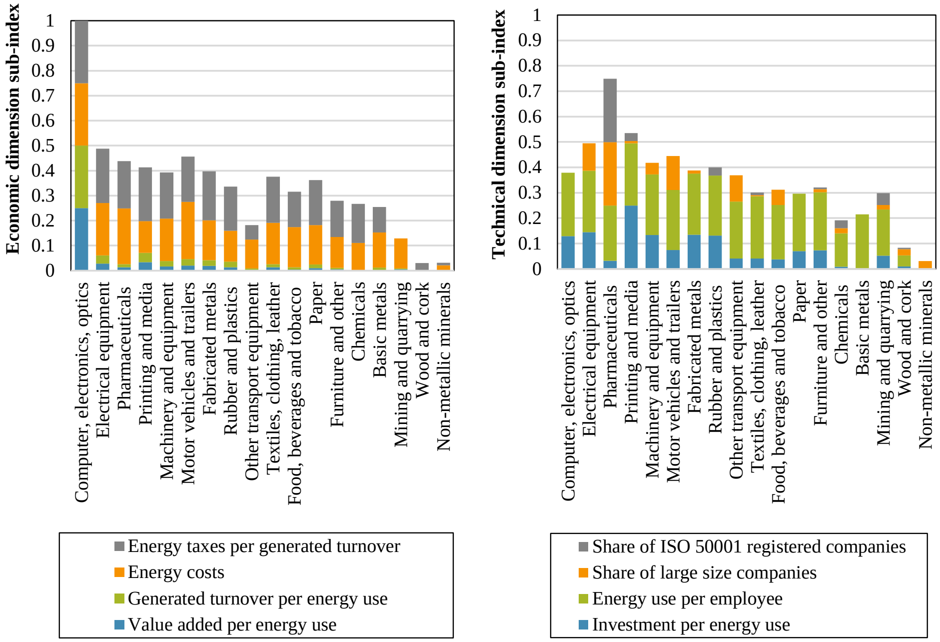
Sector	Economic dimension sub-index	Technical dimension sub-index	Environmental dimension sub-index	Energy efficiency index (EEI)
Computer, electronics, optics	1.00	0.38	0.72	0.70
Electrical equipment	0.49	0.50	0.58	0.52
Pharmaceuticals	0.44	0.75	0.37	0.52
Printing and media	0.41	0.54	0.56	0.50
Machinery and equipment	0.39	0.42	0.64	0.48
Motor vehicles and trailers	0.46	0.44	0.53	0.48
Fabricated metals	0.40	0.39	0.51	0.43
Rubber and plastics	0.34	0.40	0.53	0.42
Other transport equipment	0.18	0.37	0.58	0.38
Textiles, clothing, leather	0.38	0.30	0.40	0.36
Food, beverages and tobacco	0.32	0.31	0.44	0.36
Paper	0.36	0.30	0.39	0.35
Furniture and other manufacturing	0.28	0.32	0.42	0.34
Chemicals	0.27	0.19	0.54	0.33
Basic metals	0.25	0.21	0.48	0.32
Mining and quarrying	0.13	0.30	0.28	0.24
Wood and cork	0.03	0.08	0.56	0.23
Non-metallic minerals	0.03	0.03	0.06	0.04
Average	**0.34**	**0.35**	**0.48**	**0.39**

Units of measurement of each dimension: 1.0 being the highest and 0.0 the lowest grade

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), machinery and equipment manufacturing (0.48) sectors. Five leading sectors reached dominating values in each of the dimension sub-indices which consequently lead to the higher aggregated 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. Meaning 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), chemicals and chemical products manufacturing (0.33) sectors. Average EEI values ranging from 0.34 to 0.48 were obtained for the rest of the sectors included in the scope of this study.

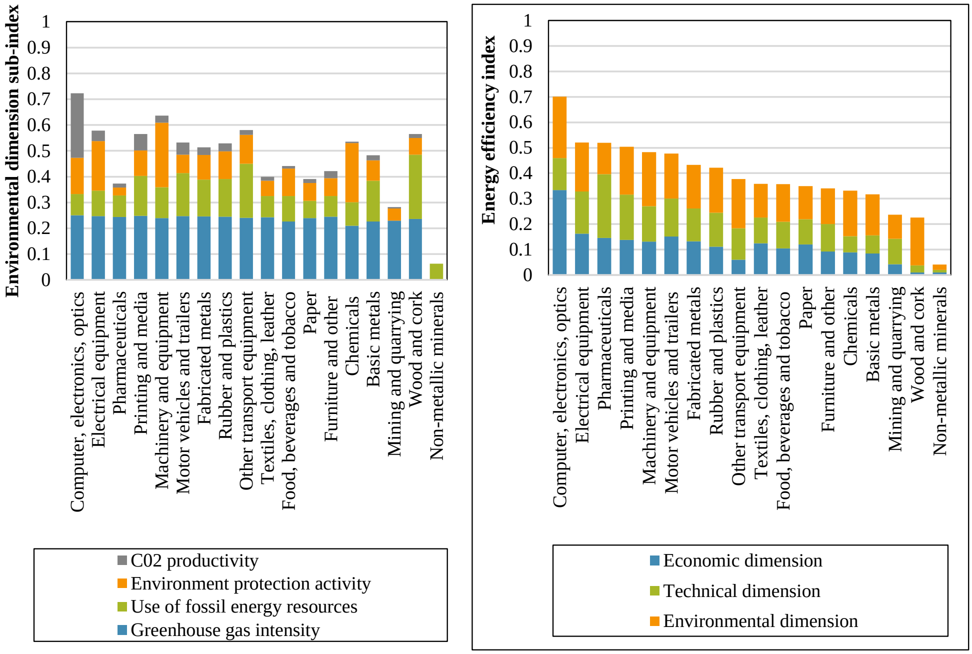
Manufacture of computer, electronic and optical products achieved the highest EEI score, mainly because of the high values it reached in economic and environment sub-dimensions. It is explained by the sector's ability to produce high value-added products with relatively low energy inputs. The sector is knowledge-intensive since it has a strong science base and is highly reliable on human capital and intellectual property thus, the economic value that the sector generates surpass the energy inputs that are required in the product manufacturing process. The second highest EEI score was obtained in the electrical equipment manufacturing sector, followed by basic pharmaceutical products and preparations manufacturing, printing and reproduction of recorded media, machinery and equipment, motor vehicles and trailers manufacturing sectors. These sectors scored similarly on all the sub-dimensions except for basic pharmaceutical products and preparations sector that presented significantly higher results in technical sub-dimension. The results indicate that manufacturing more complex and knowledge-intensive or lightweight products result in higher energy efficiency [115].

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. As a result, 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 that is measured by the generated value added and turnover per unit of energy consumed. 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.



(1) Economic dimension sub-index

(2) Technical dimension sub-index



(3) Environmental dimension sub-index

(4) Energy efficiency index

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. Except for the last group that represents time period from 2015 to 2019 that includes 4-year time interval. Since there was no data on 2020 yet available, year 2019 values were the latest available data that was included in the study. Fig. 3.2. shows the results of the decomposition analysis in combination with the CO_2 growth rates during the representative period.

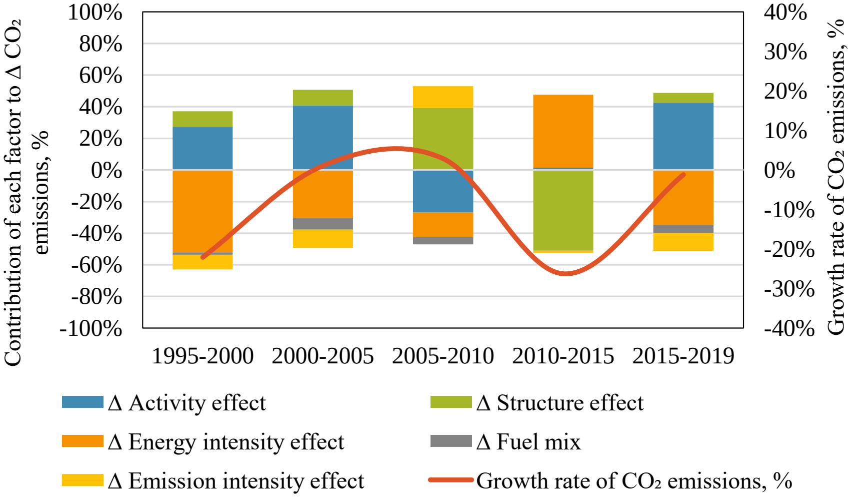


Fig. 3.2. Aggregated decomposition analysis results for the time periods.

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%. It can be concluded that CO_2 reduction in the manufacturing industry has stagnated in recent years and there has been little improvement in the last 5 years.

Significant differences are observed between periods. Table 3.2. summarizes the main events during the analyzed time intervals that influenced change in CO_2 emissions. Fig. 3.3. illustrates year-to-year changes in the contribution of each decomposition factor to the changes in CO_2 emissions and the overall growth rate of CO_2 emissions with all subsectors included. The growth rate of CO_2 emissions is negative and shows a fluctuation pattern. However, two significant peaks are observed in the periods from 2009 to 2010 and from 2017 to 2018. The first one is explained by the recovery of the manufacturing industry after the financial crisis. However, a more detailed investigation is carried out to explain the reasons for the second peak observed in recent years.

Table 3.2

Main Events During the Representative Period Driving Change in CO_2 Emissions

Time period	Main events during the representative period driving change in CO_2 emissions
1995-2000	Period after the restoration of independence during which the entire Latvian economy, including the manufacturing industry, was significantly restructured. Significant reforms in the form of ownership and changes in the foreign trade regime affected the overall development of the manufacturing industry. Imported raw materials and energy resources were now subject to world market prices, which meant that some factories that had previously been successful due to low energy costs were no longer competitive in export markets. This forced manufacturing companies to redesign production processes and invest in energy efficiency measures.
2000-2005	The period before the financial crisis was mainly characterized by high economic growth and the increase in industrial production and energy consumption. Investments in the modernization of factories and in energy efficiency could not compensate for the effect of increasing activity, which drove up CO_2 emissions.
2005-2010	Period of the global financial crisis, during which a sharp decline in total production volumes was observed from 2006 to 2009. As a result, a significant reduction in energy consumption and emissions produced were achieved. However, in 2010, a sharp increase in industrial activity led to an increase in total CO_2 emissions during this period. A shift towards more energy intensive sectors was observed during this period. The entire industrial sector experienced a significant structural change.
2010-2015	Bankruptcy and market exit of the largest metal producer led to significant structural changes in the entire industry. The sudden decline in metal production was largely offset by the rapid expansion of the wood processing sector, which drove up energy consumption in industry.
2015-2019	Higher economic growth and rising demand in the largest export markets led to an increase in production output and caused energy consumption to rise. Although there is a positive trend in the overall decarbonization of the fuel mix and reduction of the emission factor, the overall growth rate of CO_2 emissions shows an upward trend and reduction of CO_2 is stagnating.

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 analysed 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 results prove that energy efficiency improvements are the most important strategy for the long-term development of companies to achieve energy and emission savings. 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 [116]. In total, in time period from 2015 to 2019 a larger decrease in energy intensity in manufacturing 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 from policies that might have stimulated larger energy savings and achievement of more ambitious energy efficiency targets.

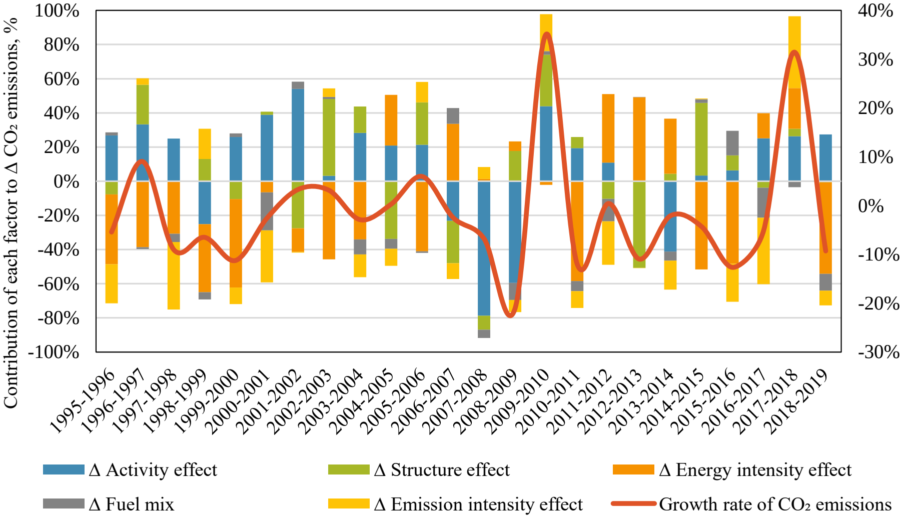


Fig. 3.3. CO_2 emission decomposition results for manufacturing industry.

Fig. 3.4. illustrates the contribution of each effect on changes in CO_2 emissions and overall change in generated CO_2 emissions in each sub-sector in a 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 year 2015. However, three sectors reported the opposite. In 2019, CO_2 emissions increased by 6% in the transport equipment production sector, by 26% in wood processing sector and by 9% in other sub-sectors compared to 2015.

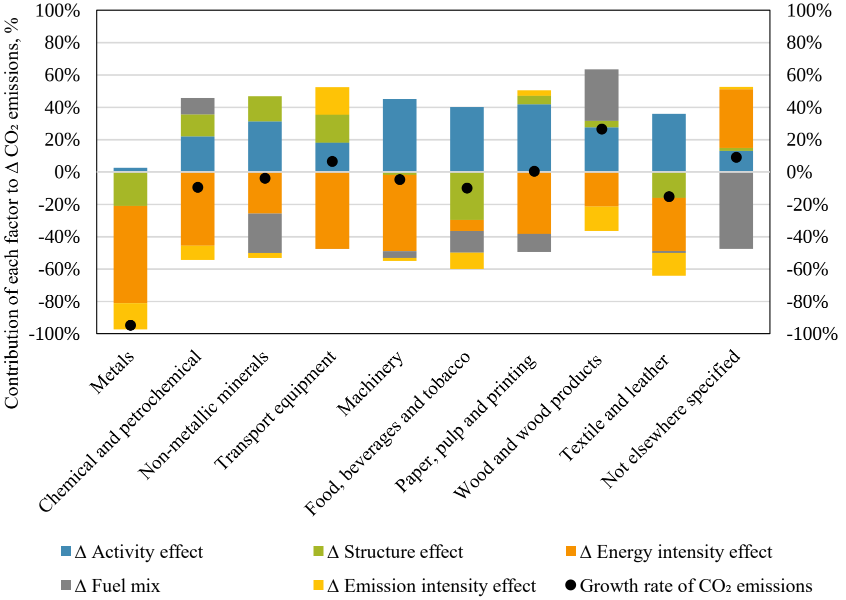


Fig. 3.4. CO_2 emission decomposition for time period from 2015 to 2019.

Energy intensity effect was the main driver that contributed to the reduction of CO_2 emissions in most of the sectors, except for not elsewhere specified sectors (plastics, rubber, furniture and other manufacturing) in the period of last five years. The wood processing sector and chemical and petrochemical production sector were the only sectors that indicated negative tendency towards increasing share of RES. Both sectors showed the opposite trend in their fuel mixes, indicating a decrease of RES in total energy mix. The results show that despite significant energy efficiency improvements in these sub-sectors, total rise in industrial activity, structural effect, and fuel mix effect counteracted energy intensity effect. Therefore, current energy efficiency improvements could not compensate for these effects which drove up the overall CO_2 emissions at much higher pace than implemented energy efficiency measures.

The structural effect shows the overall change in the contribution of a particular sector to total industrial activity. That is, if the structural effect is positive, then total industrial activity in the sector has increased and so has the total contribution to total industrial value added. On the other hand, a negative value means that the sector's contribution to the total value added generated has decreased. The results show that the share of metals production sector, food processing sector, and textile production sector in total industrial generated value added has decreased. This structural effect also contributed to the achievement of higher CO_2 reductions in the sector. On contrary, chemicals production sector, non-metallic mineral production sector, and transport equipment production sector have raised their contribution to the overall generated industrial added value over the period from 2015 to 2019.

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 [116]. Latvia's wood processing sector has seen exports increase by 82% in the last decade (over the period 2010-2019) [117] 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 [42].

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 the total fuel mix, signaling a negative trend. An increase in fossil energy consumption in the wood sector was observed during the period from 2014 to 2018. In part, this could be explained by the fact that 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.

In addition, a correlation analysis is performed to investigate the relationship between the volumes of wood products produced and the RES share in the energy balance of the wood processing sector, as shown in Fig. 3.5. The results for the period from 2013 to 2019 show a strong correlation ($R^2 = 0.9059$) with a downward slope between the two variables. The correlation analysis confirms that the increase in industrial activity in the wood processing sector caused the share of RES to decrease. The exception of 2019 can be explained by the fact that in 2019 in Latvia was observed a winter with mild temperatures, therefore there was also a lower demand for wood products, including pellets.

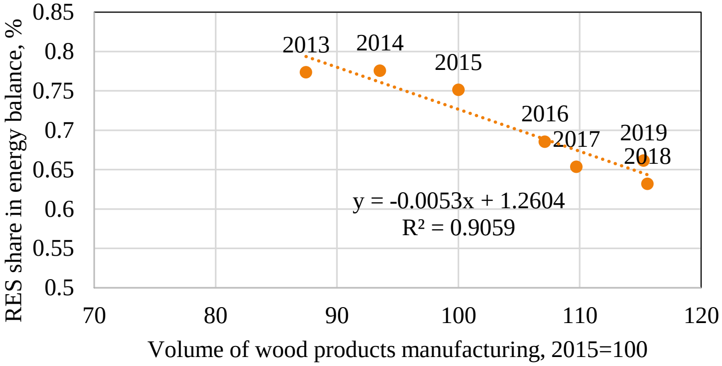


Fig. 3.5. Correlation analysis between wood production amounts and share of RES.

These insights suggest that in order to enhance industry’s overall energy efficiency performance, extra attention should be put on wood processing and non-metallic minerals production sectors since both sectors have the highest concentration and impact in the overall portfolio of manufacturing industry sectors in Latvia. However, both sectors demonstrated the worst EEI values.

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 industrial energy policy as suggested in the study by [118].

The results of this study suggest that 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 [119]. 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 [119] [118].

3.2. Transport sector

The methodological framework of transport sector analysis was based on three main pillars. First, a composite transport sustainability index was constructed for cross-country comparison of the current level of sustainability of transport infrastructure in European countries. Second, an LMDI decomposition analysis was conducted to measure the changes in transport-related GHG emissions for each country driven. Finally, an analysis of policy instruments in the transport sector was conducted to examine the measures that countries have implemented to promote the transition to carbon neutrality in transport systems.

3.2.1. Composite transport sustainability index

The transport composite sustainability index incorporated 15 indicators grouped into four dimensions: mobility, sustainability, innovation, and environment. First, the results for each sub-dimension were analyzed separately. Then, the aggregated index values were examined in detail. The higher the indicator, sub-index, and aggregated index value achieved, the higher the level of sustainability is in the respective country. The results showed two main benchmarks – the average value and the lowest value. The average value represents the average subindex value of all countries in the respective dimension and was calculated as the arithmetic mean of all values. The lowest value represents the lowest subindex value among the analysed countries, which was determined by a minimum value function in the data set. Fig. 3.6. illustrates mobility dimension sub-index values. Mobility dimension indicators describe the socio-economic aspects of transport system sustainability.

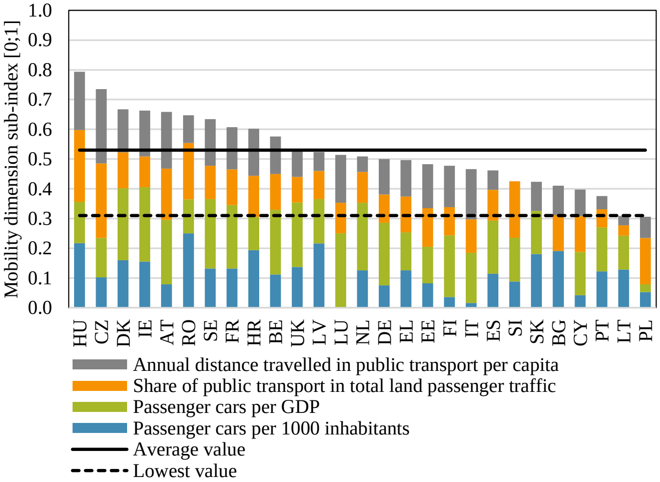


Fig. 3.6. Mobility dimension sub-index.

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 in Hungary the use of public transport is more developed and the share of private cars in total passenger transport is lower. High scores were also shown by the Czech Republic and Ireland, which scored high on almost all indicators, as did Hungary. On the other hand, the lowest values of the mobility sub-index were observed in Poland and Lithuania. Although Poland has a relatively high share of public transport in total land passenger transport, the high number of passenger cars per capita and GDP did not allow Poland to achieve higher and more competitive scores in this sub-index category. In turn, the critical aspect for Lithuania is the low public transport intensity, which prevented Lithuania from obtaining a higher score in the mobility sub-index. 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. 3.7. shows the sub-indices of the sustainability dimension for all the countries studied. This dimension included four sustainability indicators assessed by the European Commission and the World Economic Forum – the quality of roads, the hours spent annually in congestion, the productivity of implementing EU transport directives, and consumer satisfaction with urban transport.

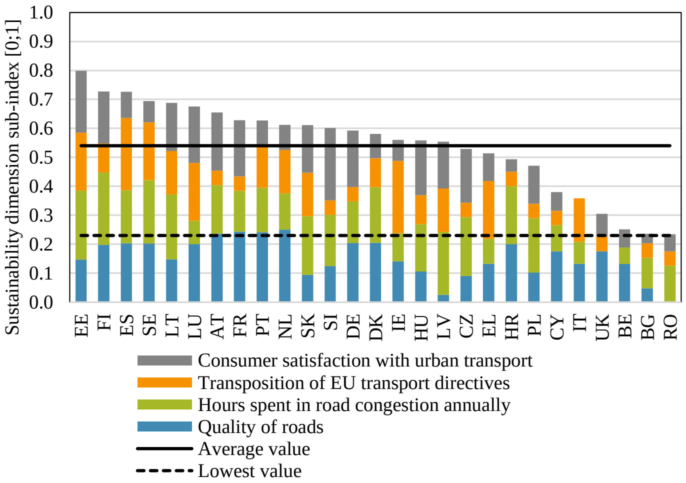


Fig. 3.7. Sustainability dimension sub-index.

The highest score on the sustainability dimension sub-index was achieved by Estonia, which scored high in all indicators except the quality of roads. Slovakia scored highest in consumer satisfaction with urban transport. Still, low scores for transposition of EU transport directives and quality of roads prevented it from achieving a higher sustainability sub-index score. 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 sub-index. 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. In addition, 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. 3.8. 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 in all indicator positions of the innovation dimension.

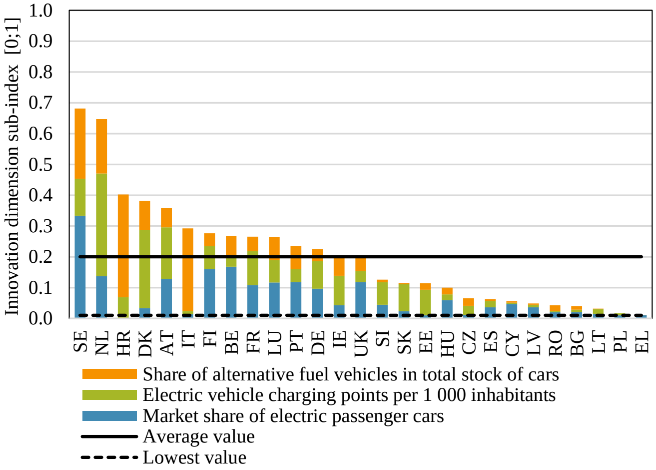


Fig. 3.8. Innovation dimension sub-index.

Fig. 3.9. illustrates the sub-indices of the environmental dimension for all countries included in the study. All countries except Sweden hade 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.

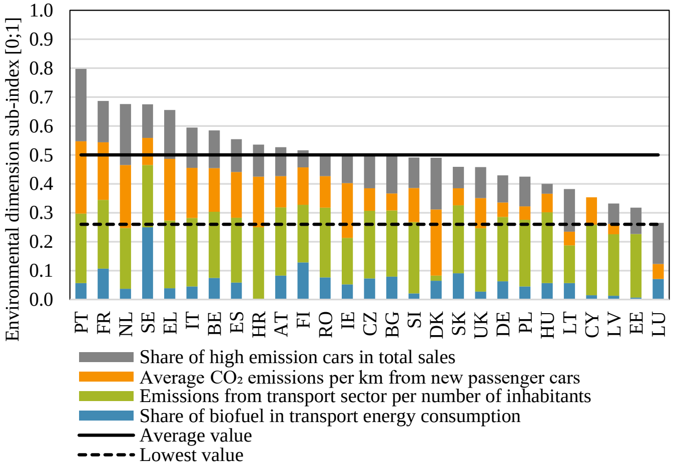


Fig. 3.9. Environmental dimension sub-index.

Fig. 3.10. shows the results of the final transport composite sustainability index. Based on the results, it was possible to identify the most critical aspects for all countries that impact a higher level of sustainability. The innovation and environmental dimensions had the lowest scores compared to the mobility and sustainability dimensions. 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,

however, 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. Table 3.3. summarizes the results of the composite transport sustainability index and sub-indices.

Table 3.3

Results of Composite Transport Sustainability Index and Sub-Indices

Country	**Mobility dimension sub-index**	**Sustainability dimension sub-index**	**Innovation dimension sub-index**	**Environmental dimension sub-index**	**Composite transport sustainability index**
SE - Sweden	0.16	0.17	0.17	0.17	0.67
NL - Netherlands	0.13	0.15	0.16	0.17	0.61
AT - Austria	0.16	0.16	0.09	0.13	0.55
FR - France	0.15	0.16	0.07	0.17	0.55
DK - Denmark	0.17	0.15	0.10	0.12	0.53
PT - Portugal	0.09	0.16	0.06	0.20	0.51
HR - Croatia	0.15	0.12	0.10	0.13	0.51
FI - Finland	0.12	0.18	0.07	0.13	0.50
IE - Ireland	0.17	0.14	0.05	0.12	0.48
HU - Hungary	0.20	0.14	0.02	0.10	0.46
CZ - Czechia	0.18	0.13	0.02	0.12	0.46
ES - Spain	0.12	0.18	0.02	0.14	0.45
DE - Germany	0.13	0.15	0.06	0.11	0.44
LU - Luxembourg	0.13	0.17	0.07	0.07	0.43
EE - Estonia	0.12	0.20	0.03	0.08	0.43
IT - Italy	0.12	0.09	0.07	0.15	0.43
BE - Belgium	0.14	0.06	0.07	0.15	0.42
EL - Greece	0.12	0.13	0.00	0.16	0.42
SI - Slovenia	0.11	0.15	0.03	0.12	0.41
SK - Slovakia	0.11	0.15	0.03	0.11	0.40
UK - United Kingdom	0.13	0.08	0.05	0.11	0.37
LV - Latvia	0.13	0.14	0.01	0.08	0.36
RO - Romania	0.16	0.06	0.01	0.13	0.36
LT - Lithuania	0.08	0.17	0.01	0.10	0.35
PL - Poland	0.08	0.12	0.00	0.11	0.30
CY - Cyprus	0.10	0.10	0.01	0.09	0.30
BG - Bulgaria	0.10	0.06	0.01	0.12	0.30

The composite transport sustainability index results were classified into four groups of sustainability levels, as shown in Fig. 3.10. The first group included countries with a high sustainability level (with a composite sustainability index score equal or above 0.6), such as Sweden (0.67) and the Netherlands (0.61), which have achieved composite transport sustainability index values significantly higher than the average value and who have showed outstanding results compared to other countries. The second group included countries with a moderate level of sustainability, whose composite transport index values ranged between 0.44 (Germany) and 0.55 (Austria) which was equal to or above the average composite index score of all countries analyzed. The third group included countries with a low level of transport sustainability, whose composite transport sustainability index was below the average value of 0.44. The fourth group included countries with very low levels of sustainability (with a composite sustainability index score equal to or below 0.3), with a composite transport sustainability index of 0.3. The fourth group consists of three countries – Poland, Cyprus, and Bulgaria.

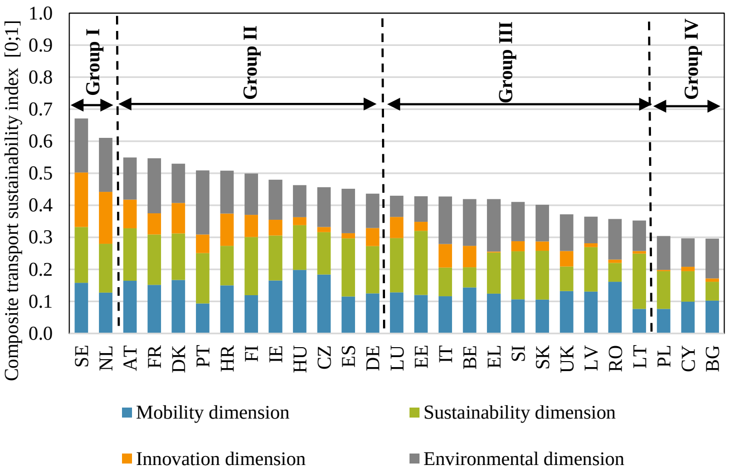


Fig. 3.10. Composite transport sustainability index.

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. 3.11 illustrates the LMDI decomposition analysis results of GHG emissions of the transport sector from 2010 to 2019 for each country. The results for each country in thousand tons of CO_2 equivalent were also reflected in Table 3.4.

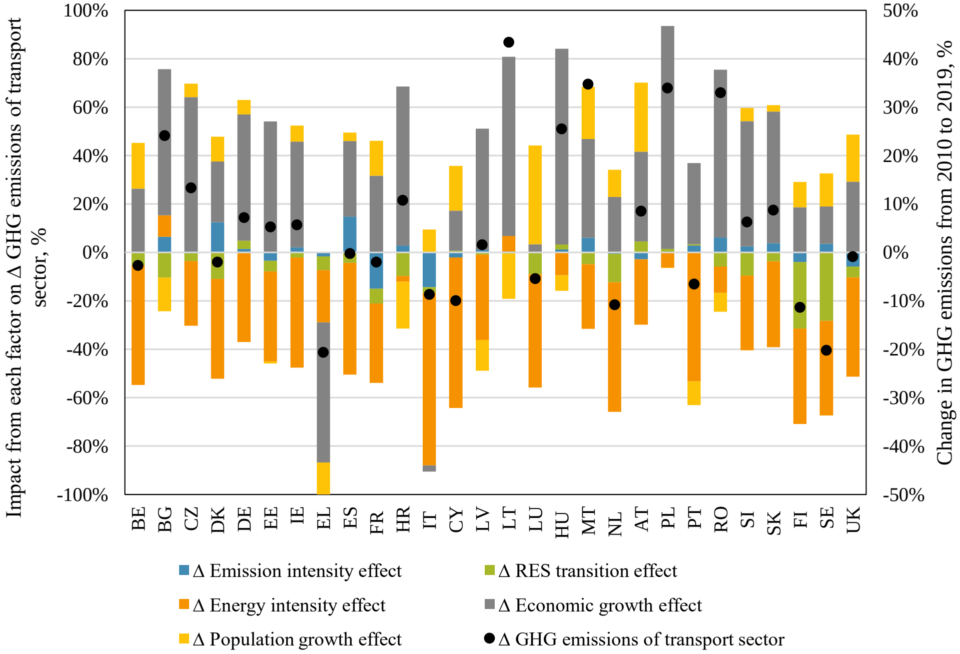


Fig. 3.11. LMDI decomposition analysis results of GHG emissions of transport sector from 2010 to 2019 (thousand tons of CO_2 equivalent) for each country.

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%).

Table 3.4

Decomposition of GHG Emissions of Transport Sector from 2010 to 2019 (thsd tons of CO_2 eq)

Country	**Δ Emission intensity effect**	**Δ RES transition effect**	**Δ Energy intensity effect**	**Δ Economic growth effect**	**Δ Population growth effect**	**Δ GHG emissions in the transport**	**% change from 2010 to 2019**
BE - Belgium	-11.9	-399.0	-3764.1	2011.0	1442.0	-721.9	-2.7%
BG - Bulgaria	243.8	-394.0	334.7	2274.6	-522.7	1936.5	24.1%
CZ - Czechia	-20.2	-181.5	-1519.6	3643.5	318.3	2240.5	13.3%
DK - Denmark	747.5	-660.6	-2482.5	1509.0	618.1	-268.6	-2.0%
DE - Germany	631.0	1442.5	-15809.3	22238.4	2571.7	11074.2	7.2%
EE - Estonia	-51.2	-63.6	-545.4	793.8	-13.4	120.2	5.3%
IE - Ireland	282.5	-278.3	-6067.6	5828.6	889.2	654.4	5.7%
EL - Greece	-78.5	-259.7	-1006.1	-2685.6	-614.3	-4644.2	-20.7%
ES - Spain	3756.9	-1110.4	-11699.2	7909.3	917.3	-226.2	-0.2%
FR - France	-5279.8	-2122.7	-11542.6	11119.6	5096.7	-2728.8	-2.0%
HR - Croatia	48.7	-168.4	-41.3	1137.0	-334.0	642.1	10.8%
IT - Italy	-1780.9	-294.1	-8829.2	-313.2	1174.0	-10043.4	-8.7%
CY - Cyprus	-17.0	6.1	-519.9	137.7	154.8	-238.3	-10.0%
LV - Latvia	23.4	-20.9	-843.0	1197.6	-304.8	52.3	1.6%
LT - Lithuania	10.4	-13.3	200.2	2283.0	-577.3	1903.0	43.4%
LU - Luxembourg	-7.2	-265.3	-1420.1	102.9	1235.6	-354.0	-5.4%
HU - Hungary	53.3	89.8	-412.4	3539.3	-283.7	2986.1	25.5%
MT - Malta	31.9	-25.7	-140.0	213.9	113.5	193.7	34.7%
NL - Netherlands	-64.1	-1399.2	-6348.0	2724.1	1328.8	-3758.4	-10.8%
AT - Austria	-133.7	215.6	-1286.2	1764.7	1362.3	1922.6	8.5%
PL - Poland	74.1	210.8	-1195.1	17734.0	-59.8	16764.0	34.0%
PT - Portugal	134.0	27.1	-2524.4	1589.2	-470.1	-1244.3	-6.6%
RO - Romania	568.9	-536.0	-1003.2	6396.1	-726.9	4698.9	33.0%
SI - Slovenia	42.5	-164.7	-532.6	894.0	92.7	331.9	6.3%
SK - Slovakia	113.4	-110.9	-1061.6	1627.4	80.4	648.7	8.7%
FI - Finland	-138.7	-948.7	-1365.4	646.5	362.1	-1444.2	-11.4%
SE - Sweden	427.0	-3386.8	-4687.1	1846.8	1639.6	-4160.5	-20.2%
UK - United Kingdom	-2306.8	-1793.5	-16231.2	11551.8	7713.9	-1065.8	-0.9%
Total	**-2700.9**	**-12605.4**	**-102342.2**	**109715.0**	**23203.9**	**15270.5**	**1.6%**

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 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 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 prevented for the achievement of higher GHG emission cuts in the transport sector.

The results showed substantial differences in the average composite sustainability index scores achieved between the Eastern, Western, and Nordic countries, which was also reflected in the GHG emission reductions achieved over a 10-year period from 2010 to 2019. Table 3.5 summarizes the main results of the composite sustainability index and decomposition analysis by grouping the results into two main country groups – Nordic European countries, Western European countries, Eastern European countries.

Table 3.5

Summary Results of the Composite Sustainability Index and Decomposition Analysis

	Mobility dimension sub-index	**Sustainability dimension sub-index**	**Innovation dimension sub-index**	**Environmental dimension sub-index**	**Composite transport sustainability index**	**GHG change from 2010 to 2019, %**
Nordic Europe (SE, FI, DK)	0.15	0.17	0.11	0.14	0.57	-12.6%
Western Europe (NL, FR, PT, ES, DE, LU, IT, BE, EL, UK, AT, IE)	0.13	0.14	0.06	0.14	0.47	-1.5%
Eastern Europe (HU, CZ, SK, RO, PL, BG, EE, LV, LT, HR, SI, CY)	0.13	0.13	0.02	0.11	0.39	19.7%

Country groups with higher average composite sustainability index scores, such as the Nordic and Western European countries, have also achieved the highest reductions in CO_2 emissions in the transport sector. In contrast, the Eastern European country group, which indicated the lowest average composite sustainability index score, hasn't achieved a reduction in CO_2 emissions in the transport sector, but showed a significant increase. The Nordic countries outperformed other countries by on average indicating significantly higher scores in all dimensions of transport sustainability with the highest dominance in innovation and sustainability dimension indicators. While the Eastern European countries have, on average, reached almost the same level as the Western European countries in the indicators of mobility and the sustainability dimension, they still lagged significantly behind in the indicators of the environmental and innovation dimension.

Due to the different national renewable energy targets, development strategies, political incentives and priorities set in the transport sector in the individual European countries, different development trends in the transport sector can be observed from country to country. Although the Renewable Energy Directive introduced in 2009 set the same target for all EU member states, namely, to achieve a 10% share of renewable energy in total energy consumption in the transport sector by 2020, countries have achieved very different results by 2020 [120]. Of the 27 EU Member States, only 12 countries met this target, with Sweden (31%) and Finland (13.4%) reporting the highest levels. Majority out of which nine are Eastern European countries indicated RES share in transport below 10% by 2020, with the lowest results in Greece (5.3%), Lithuania (5.5%), Poland (6.6%), Croatia (6.6%) and Latvia (6.7%) [120]. The part of these deviations in achieved RES targets by EU-27 countries can be explained by the degree of strictness of national RES targets in each country and the interest, intentions, and support of national governments in setting more ambitious decarbonization targets for the transport sector. In general, the majority of EU countries have not been strict to take strong action to mitigate climate change from activities in the transport sector, which is reflected in the results of the study, where the majority of countries have increased their transport-related CO_2 emissions and have not met the binding renewable energy target.

Sweden, which is the absolute leader in the EU in the share of RES in transport and which have achieved the largest reductions in transport-related CO_2 emissions over the study period, has set ambitious RES targets for transport sector and has used various policy mechanisms to incentivize the transition to low-carbon fuels, such as setting a carbon tax on fuels, which has been in place since 1991 (to limit fossil fuel consumption), and introducing tax exemptions for sustainable biofuels (to encourage the development of alternative fuel infrastructure) [120].

The results of this study showed that innovation dimension is the main cornerstone that differentiates Eastern and Western European countries from Nordic countries which lead in electric and alternative fuel vehicle market and infrastructure. In the Nordic countries, institutional support and policy incentives to promote the development of energy efficient and low-carbon transport systems have been in place since the 1990s. Sweden, for example, introduced an energy and carbon tax on transportation fuels in 1995, Finland developed and implemented an environmental driving education program in driving schools in 1994, and Denmark introduced an environmental fee for vehicle owners in 1999, charging annual fees based on average fuel consumption. However, in most Eastern and Western European countries, carbon neutrality in the transport sector has received greater attention only since the 2010s [121]. Therefore, strong institutional support and policy incentives are needed for the development of a sustainable and carbon-neutral national transportation infrastructure. Institutional support, however, will only be effective if combined with policy mechanisms and instruments aimed at improving general knowledge and awareness of environmental issues in society. Environmental awareness and sense of public responsibility is directly linked with one’s decision making which also includes the choice of daily transportation habits

The results of this study showed that, on average, Eastern European countries performed significantly worse than Nordic and Western European countries in the indicators of the environmental dimension. The poor environmental performance of Eastern European countries was also reflected in the energy efficiency indicators monitored by Odysee Mure, which showed similar results for CO_2 intensity of transport (kCO_2/EUR2010) and specific fuel consumption (l/100km) indicators. The data showed that the CO_2 intensity of transport in Eastern European countries is almost three times higher than in Nordic countries and twice higher than in Western European countries. A similar trend was observed in the vehicle efficiency indicator, where Latvia had the highest average specific fuel consumption of 9.41 l/100 km and Luxembourg had the lowest average specific fuel consumption of 5.5 l/100 km from the available data [122] .

The lower energy efficiency and higher carbon intensity of the transport sector in Eastern European countries could be due to the significantly older average stock of cars in Eastern European countries compared to Western European countries. Eurostat 2020 data [50] showed that several EU countries have a high share of old passenger cars in the total stock, with the highest share of passenger cars over

20 years old in Poland (40%) and Estonia (32.7%). In contrast, the share of passenger cars with an age of only two years or less was reported to be highest in Luxembourg (22.0%) and France (16.7%) [50]. Eastern European countries are usually a secondary car sales market, where used cars are mostly exported from Western European countries [123]. Therefore, the average vehicle stock in Eastern European countries is older and less efficient. The lower average income level of Eastern European countries is one of the reasons why the secondary car sales market is more prevalent in Eastern Europe.

3.2.3. Policy measures to promote transport decarbonization

Assessing the impact of policies is a significant challenge, especially in the transport sector, where decarbonization is based on technical solutions (e.g., converting the fleet from fossil fuels to electricity) and changing habits. The method described and its application for the analysis and comparison of EU countries was an attempt to highlight those instruments of sustainable transport policy that have yielded the best results so far. This research highlighted several essential policy measures (directions) for transport decarbonization from the analysis. They were described below, together with an in-depth analysis of these policies in the best-performing countries. Various data sources have been used to analyze policy measures, including IEA and Odysee Muree transport policy databases, national energy and climate plans, and country-specific policy planning documents.

Facilitate the transition from private cars to public transport

The role of public transport in the composite transport sustainability index was primarily reflected in three indicators: annual distance travelled in public transport per capita, the share of public transport in total land passenger traffic, and consumer satisfaction with urban transport.

The Czech Republic and Hungary obtained the highest scores for two of the three indicators – Share of public transport in total land passenger traffic and Annual distance travelled in public transport per capita (0.25 and 0.25 for the Czech Republic and 0.24 and 0.2 for Hungary, respectively). Austria also had a high score in the second indicator (0.19). Meanwhile, Slovenia and Estonia scored the best for the indicator Consumer satisfaction with urban transport (0.25 and 0.21, respectively). The Czech Republic, Germany, France, Luxembourg, Hungary, and Finland performed equally well in the user satisfaction indicator and closely followed the two leaders (0.19).

Several common trends characterize leading countries. Firstly, there is the emphasis on rail transport as the backbone of the transport system. The measures aim to continuously improve the railway infrastructure and connect it to other modes of transport. The Czech Republic, Hungary, and Austria also use the metro, significantly increasing the number of kilometres travelled by public transport in densely populated areas.

Secondly, there is a strong link between national and municipal strategic planning levels. Municipalities are closest to their citizens. Strategic municipal mobility plans ensure the promotion of the use of public transport following the conditions of the particular place. For example, in the Czech Republic, there is a requirement that Strategic Sustainable Urban Mobility Plans (SUMPs) should be developed and regularly updated in cities with a population of over 40,000 [124]. Also, Austria has a well-established urban transport planning framework that incorporates SUMPs [125]. though their implementation is voluntary. The Austrian example also demonstrates cooperation between the national and municipal planning levels through the national ‘klimaaktiv mobil’ climate protection program, which offers cities and municipalities consultation and financial support to implement mobility management measures [126]. The role of municipalities and cities is critical to ensure a gradual transition to modern zero-emission or alternative-fuel vehicles and to implement measures to promote public transport. One of the essential indicators is consumer satisfaction with public transport. Slovenia and Estonia showed the highest score on this indicator in the composite transport sustainability index (0.25 and 0.21, respectively). Satisfaction with the public transport service is usually determined by indicators such as the availability and accessibility of public transport, frequency and connectivity, travel time and safety, information, comfort, and price [127]. Slovenia, which had one of the highest shares of public transport in total land passenger transport in Europe, has made the improvement of public transport infrastructure one of the key strategic priorities of Slovenia's national energy and climate plan. Adjusting timetables, integrating urban transport and establishing a public passenger transport operator were among the specific measures aimed at making the use of public transport more attractive to consumers [128]. Financial incentives in the form of subsidized tickets are used to increase the competitiveness of public transport [129].

Estonia is an interesting example since it has investigated the free public transport introduced in Tallinn for locals. Results showed that the share of public transport use stopped declining for a couple of years [122]. However, the free public transport policy did not reach its goal of reducing car journeys (still, most commuting is done by car) [130]. At the same time, this was not an optimal indicator, as the attitude of the existing public transport users towards service and quality could be seen. Continuous improvements in public transport would deter existing users from leaving and increase their positive evaluation. However, it is just as important (if not more important) to attract new public transport users who previously used private cars. Several studies on modal shift from private cars to public transport suggest that optimal policy instruments should strike a balance between pull (i.e. "carrot" and push (i.e. "stick") policies [131], [132], [133] i.e., public transport improvements and the burden on car users. Previous research shows that the motivation to choose public transport over the car was low [134], [135]. Further research and evaluation would be desired on soft policies, especially for mode shift (information campaigns, test drives, etc.)

Promotion of electric mobility and infrastructure

In the scope of this study, the dimension of electric mobility promotion and infrastructure was characterized by two indicators: market share of electric passenger cars and electric vehicle charging points per 1000 inhabitants.

Sweden had the highest score for the market share of electric passenger cars (0.33), followed by Belgium, Finland, the Netherlands, and Austria. However, the score for these countries was significantly lower (0.13-0.17). It should be noted that the value of this indicator for several countries was 0 or very close to it (Croatia, Estonia, Poland, Greece, Czech Republic, Italy, Lithuania). It means that the progress in these countries in electric mobility infrastructure development was significantly lower than in leading countries. The highest score for the electric vehicle charging points per 100 thousand people was in the Netherlands (0.33), Denmark (0.25), Austria (0.17), Sweden (0.12), and France (0.11). Similarly, for the indicator of the market share of electric passenger cars, the value was 0 or very close in several countries (Greece, Cyprus, Romania, Poland, Bulgaria, Latvia, Italy). The results of the composite sustainability index were consistent with the results of the LMDI decomposition analysis, which showed that the most significant transition to zero-emission vehicles over a ten-year period was observed in Sweden, Finland, the Netherlands.

The Netherlands, Belgium, Sweden, and several other countries have seen a sharp increase in electric cars since 2018, driven by well-designed and implemented policies. The Netherlands has the highest number of electric cars per capita in the European Union. The Netherlands also has the most developed charging infrastructure. There are about 150 charging stations per 100 km^2 of the country's territory. In comparison, Germany, which ranked second for the number of electric cars per capita, had only 12 charging stations per 100 km^2.

The rapid development of electric vehicles can be observed in countries with long-term energy policies that indicates the importance of electric vehicles for decarbonizing the transport sector and prioritize electric mobility. For example, in the Netherlands, the country's long-term goal is to make all new cars CO_2-free by 2030. The focus for achieving this ambitious goal is on electrical mobility.

In countries where the development of electric mobility was already well advanced, a balanced spectrum of policy instruments, both penalty (i.e. “stick”) and reward (i.e. “carrot”) measures can be observed. The main reward and pull measure (i.e. “carrot”) is financial support to purchase an electric vehicle. Support for installing charging stations for different target groups, including businesses and individuals, is also provided in several countries, including the Netherlands and Belgium. Registration and operating tax exemption are widely used in countries with a high number of electric vehicles. Companies' tax incentives are another successful instrument used in the Netherlands, Germany, and Sweden.

The penalty and push (i.e. "stick") instruments focus mainly on introducing a higher tax burden on CO_2-emitting vehicles to motivate users to choose electric vehicles. In Denmark, Belgium, Finland, and many other countries, the vehicle registration tax is dependent on CO_2 emissions. Another instrument that targets the use of internal combustion engines and the transition to electric vehicles is the introduction of so-called green zones in cities, where only low-carbon or zero-emission vehicles are allowed to enter.

Most EU countries use similar instruments to promote electrical mobility. The main differences are the number of instruments and their monetary value (e.g., the amount of reimbursement granted). In countries with significant progress in the development of electric mobility, instruments can be observed that target not only individual end-users but also larger groups such as municipalities or associations. In all these countries (with advanced electric mobility), support for infrastructure development and research funding in electrical mobility is a mandatory requirement. In Sweden, for example, the value of fringe benefits for company cars is ensured to encourage the purchase of low-emission vehicles at the corporate level and thus achieve a higher penetration of environmentally friendly vehicles [136].

Promotion of other alternative fuels

In the context of the study, the dimension of the promotion of other alternative fuels was characterized by two indicators: the share of alternative fuel vehicles in the total passenger car fleet and the share of biofuels in energy consumption in transport.

Sweden had the highest value for the indicator measuring the share of biofuels in energy consumption in transport (0.25), followed by Finland, France, and Slovakia, but with significantly lower values (0.09-0.13). The value of this indicator was 0 or very close to it for several countries such as Croatia, Estonia, Latvia, and Cyprus. The highest values for the indicator measuring the share of alternative fuel vehicles in the total vehicle stock were found in Croatia (0.33), Italy (0.27), Sweden (0.23), and the Netherlands (0.18). In the remaining countries, this value was significantly lower. For several countries, the value of this indicator was 0 or very close to it (Lithuania, Greece, Poland, Latvia, Slovakia, etc.), which means that these countries were significantly behind in the transition to alternative fuels compared to the leaders.

Sweden and Finland are among the countries with the highest biofuel blends of around 21%. This is the main reason for the high share of biofuels in total final energy consumption in the transport sector. Finland and the Netherlands also have relatively high biofuel blending requirements (20% and 17%, respectively). Another successful instrument used in several countries with high biofuel use (e.g., Sweden) is the introduction of specific CO_2 tax systems for fuels. The principle is to increase taxes on fossil fuels and decrease taxes on biofuels. The lower the CO_2 content of biofuels, the greater the tax benefits. The application of such a mechanism helps increase the economic attractiveness of biofuels. In Sweden, for example, pure biodiesel is also actively used without fossil fuels (about 5% of total energy consumption in transport).

Countries with a high share of biofuels in their overall transport energy balance also have in common that they actively use biofuels and promote the production of biofuels in the country through a variety of instruments. The focus is on producing advanced biofuels, although the technologies used differ in some cases. For example, Sweden relies on thermochemical processes to produce biodiesel, while Finland is among the world leaders in producing bioethanol using hydroprocessing technology. Such an approach is sustainable as it brings economic and social benefits to the country and reduces CO_2 emissions by reducing the use of fossil fuels. At the same time, several countries, especially the Scandinavian countries, restrict the use of agricultural products to produce first-generation biofuels through various instruments.

Several countries are actively promoting the use of biomethane in transportation. Sweden is a leader, with biomethane accounting for about 1.5% of the country's total energy consumption. To promote biomethane, a combination of policy instruments is typically used. First, subsidies for biogas or biomethane production (Germany, Denmark, Finland, Italy). Second, non-taxation of biomethane (Sweden and Finland) or other tax incentives for both biomethane producers and users (Germany, Sweden, Netherlands, and Italy). Third, granting different feed-in tariffs for the transmission of biomethane (Germany, Denmark, Finland, Italy, and the Netherlands). As well as an additional mechanical blending of biomethane to fossil fuels and subsidies for infrastructure development.

Many countries that are actively using biomethane in transport are also supporting the use of compressed natural gas (CNG) in transport through various policy instruments. The main instruments for CNG promotion are subsidies for end-user infrastructure and reduced taxes, and the government sometimes also supports the purchase of CNG-fuelled vehicles (Italy, the Netherlands, Austria, Croatia). For both biomethane and CNG use in transport, the most significant progress has been made in countries that actively promote the use of these fuels in public transport and trucks (e.g., by limiting CO_2 emissions through public procurement) in addition to the instruments mentioned above. The promotion of hydrogen has been identified as one of the priorities in the long-term strategies of several countries. However, only a few countries are currently using policy instruments.

Promotion of energy efficiency and achievement of energy savings

In the context of the study, the energy efficiency dimension was characterized by five indicators: passenger cars per 1000 inhabitants, passenger cars per GDP, transport sector emissions per number of inhabitants, average CO_2 emissions per km of new passenger cars, the share of high-polluting emission cars in total sales.

From an energy efficiency perspective, it is crucial to ensure that the number of cars per capita is as low as possible but to increase the use of public transportation and encourage bicycles and public transportation. The passenger car per 1000 inhabitants indicator measures the concentration of passenger cars in the country's total passenger transport. It showed that Luxembourg (0.0), Italy (0.02), and Finland (0.04) are among the countries with a high concentration of passenger cars, while Romania (0.25), Hungary (0.22), and Latvia (0.22) had the lowest. However, it is essential to consider whether the low number of cars is not due to the low-income level of the population and the inability to buy a private car. This was accounted for in the indicator measuring passenger cars per GDP, which showed that Belgium (0.0) and Poland (0.03) had a high concentration of cars in relation to the country's total GDP. In contrast, Luxembourg and Ireland (0.25), Sweden (0.24), and the Netherlands (0.23) had the lowest values and therefore are less concentrated with passenger cars in total traffic.

Another essential aspect of energy efficiency in the transport sector is the promotion of low-emission vehicles in the total sales of new passenger cars to prevent the new purchase of high emission vehicles. The results showed that Estonia (0.00), Latvia (0.14), Lithuania (0.19), and Poland (0.19) had the lowest efficiency, having the highest average CO_2 emissions per km for new passenger cars. In addition, Cyprus (0.00), Hungary (0.14), and Latvia (0.28) were among the countries with the highest share of highly polluting vehicles in total sales. These results indicated that vehicles with larger engines are more preferred than energy efficiency benefits obtained by smaller and more efficient vehicles in these countries. This suggests that these countries did not have stringent policies that would limit the purchase of new high emission vehicles. In contrast, the best performing countries in promoting energy efficiency were Portugal (0.25), Denmark (0.23), and the Netherlands (0.22). These countries had the lowest values for average CO_2 emissions per km of new passenger cars. Similarly, Portugal (0.25), the Netherlands (0.21), and Denmark (0.18) had the lowest proportion of highly polluting vehicles as a proportion of total sales. The results of the LMDI decomposition analysis showed that the Netherlands, Belgium, Denmark, Italy, Sweden, Finland, France and Portugal experienced significant energy efficiency improvements over a ten-year period, which were the main reason for the decline in transport related GHG emissions in these countries.

It is usually challenging to reduce the number of cars in economically developed countries, so penalty (i.e. “stick”) policy instruments are preferred. For example, the introduction of so-called green zones in cities, where only zero- or low-emission vehicles are allowed to enter (Germany, Netherlands, Belgium). Another solution is to introduce a system of high taxes on vehicle CO_2 emissions. For example, Sweden has introduced specific taxation depending on the CO_2 emissions of the vehicle, while Finland, the Netherlands and Portugal impose a specific tax on the purchase of passenger cars . Mandatory standards are also used to control the level of specific emission intensities allowed for new vehicles. For example, Germany sets CO_2 emission standards for passenger cars and vans, as well as a passenger car label for fuel consumption. The effectiveness of this type of restrictive instruments is shown not only in reducing the number of passenger cars but also in reducing CO_2 emissions, both in terms of population and number of vehicles. Reward (i.e. “carrot”) policy instruments are also used in many countries to facilitate the transition from inefficient, low-emission vehicles to financial vehicles, such as financial support for purchasing new zero-emission vehicles and the phasing out of old, carbon-intensive vehicles. In France, for example, Bonus-malus scheme for the purchase of new vehicles (bonus-malus écologique) was developed to support consumers by subsidising the scrapping of old vehicles and subsidising clean and efficient vehicles.

Close cooperation between national and local authorities is essential to achieve results and promote energy efficiency in the transport sector to encourage the implementation of harmonized policy instruments that complement each other without creating competition, rising vehicle prices and related infrastructure, and overall fragmentation of the sector.

3.3. Energy sector

The national energy sector analysis is structured into three key segments, each addressing a crucial aspect of energy sustainability and development across EU-27 countries. First, a general energy sustainability assessment is conducted to evaluate various components of energy sustainability. This segment also examines the overall trends in reducing CO_2 emissions from fuel combustion, providing insights into the progress made by EU member states toward carbon neutrality. Next, the LMDI decomposition analysis is applied to assess the growth and development of RES electricity capacities across EU member states. Finally, the level of energy independence of each country is reviewed through LMDI decomposition analysis of changes in net energy imports across the EU.

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. 3.12. 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 achieved results below the average of 0.54.

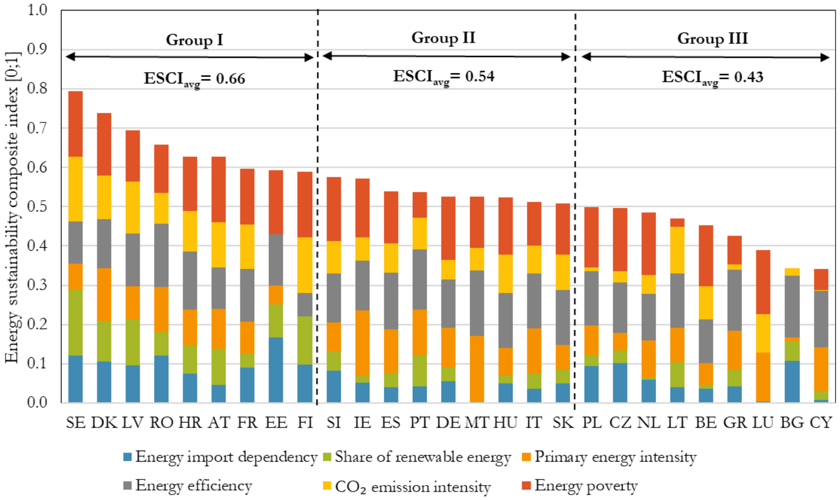


Fig. 3.12. Energy sustainability composite index (ESCI) results for EU-27 countries.

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. France's national energy sustainability is characterized by weaknesses in the share of renewable energy resources and primary energy intensity, while strengths are observed in lower energy poverty and CO_2 emission intensity. In comparison to other countries, Finland's energy sustainability is comparatively weaker due to its higher energy consumption per capita, as indicated by its energy efficiency indicator. However, Finland's energy poverty rate is relatively lower, which is its strongest aspect in terms of energy sustainability.

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 and the average ESCI score was 0.54. ESCI methodology enables the identification of primary strengths and weaknesses of individual countries, as well as the tracking of advancements towards attaining energy sustainability.

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. Changes in CO_2 emissions were decomposed using Kaya identity factors to determine which of the following factors contributed the most to the changes: changes in emission intensity, energy intensity, economic or population growth. The results indicate that all EU member states have untapped potential for improving energy sustainability. Fig. 3.13. shows the results of the LMDI decomposition analysis for all EU-27 countries.

The results show that the majority of EU countries have succeeded in reducing CO_2 emissions from fuel combustion, moving closer to overall decarbonization targets for the economy. However, eight countries showed the opposite trend, as they experienced a slight increase in energy-related CO_2 emissions. Countries that reported an increase in CO_2 emissions from fuel combustion over the 5-year period from 2015 to 2019 are Cyprus (7.27%), Lithuania (5.87%), Hungary (4.98%), Austria (3.94%), Luxembourg (3.94%), Latvia (3.90%), Slovakia (2.13%), and Poland (1.89%). The results of the LMDI analysis show that the large increase in CO_2 emissions in Cyprus is due to the large increase in economic and population growth, which has significantly increased the total demand for energy. Although a reduction in energy and emissions intensity was achieved, it was not significant enough to compensate for the increase in the overall economy. An increase in CO_2 emissions was seen in almost all sectors except industry, with the transport and services sectors being the most critical.

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, as the services, residential, and industrial sectors saw significant emission reductions.

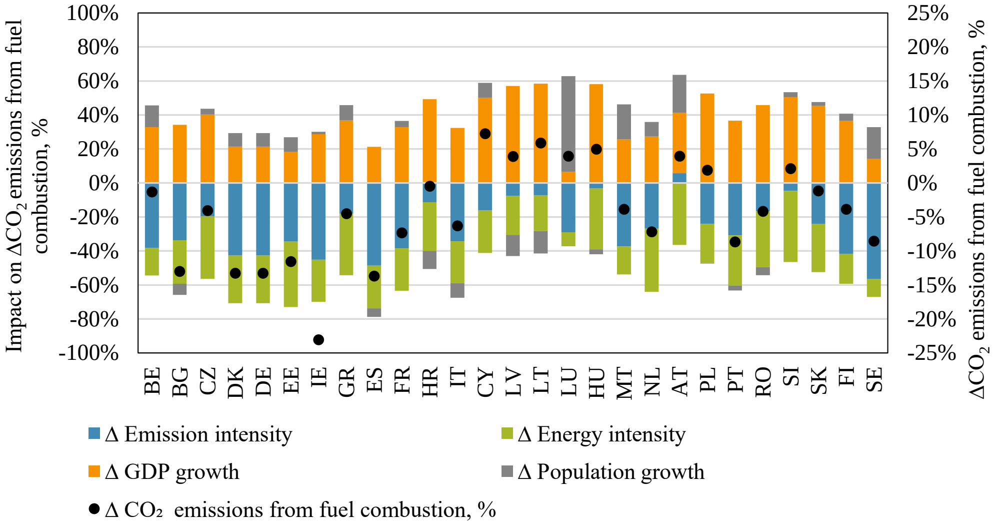


Fig. 3.13. LMDI decomposition analysis results for changes in CO_2 emissions from fuel combustion from 2015 to 2019.

The largest emission reductions from fuel combustion were achieved in Ireland (-23.05%), Spain (-13.68%), Denmark (-13.27%), Germany (-13.27%), and Bulgaria (-13.01). All of these countries achieved significant reductions in CO_2 emissions in all sectors except transport, although the increase in transport-related CO_2 emissions was slightly moderate. The common trend for these countries is significant reductions in emissions intensity, indicating strong policies toward decarbonization and green transition, while for other countries that have not achieved overall CO_2 emissions reductions, energy intensity reductions have been the most important predominant factor.

Overall, CO_2 emissions from fuel combustion in the EU decreased by 172 Mt CO_2 from 2015 to 2019. This decrease was achieved through a decrease in energy intensity (-212.02 $MtCO_2$) and emissions intensity (-211.56 $MtCO_2$). However, the impact of economic growth (229.62 $MtCO_2$) and population growth (22.28 $MtCO_2$) prevented a greater reduction in emissions.

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 results were shown for Latvia and Austria, which ranked in Group I in the ESCI but showed an increase in emissions over the period.

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. On the other hand, countries such as Ireland and Germany, which were initially ranked lower in the ESCI, have reported significant progress in decarbonization by reducing CO_2 emissions from fuel combustion. This suggests that countries that initially trailed behind in demonstrating a high proportion of renewable energy resources in their total energy balances may be more motivated and driven toward a more active transition away from fossil fuels and towards renewable energy. It may be simpler for these countries to identify regions where decarbonization activities will result in substantial emission reductions.

Countries that outperformed all others are Sweden and Denmark, which are among the most energy sustainable countries in both the ESCI and LMDI, with consistent reductions in CO_2 emissions from fossil fuels. However, the worst results were shown by Cyprus and Lithuania, which ranked exceedingly low in the initial sustainability of the energy sector compared to other EU countries and encountered an increase in CO_2 emissions from fuel combustion from 2015 to 2019.

3.3.2. LMDI decomposition analysis of renewable energy deployment over years

Fig. 3.14. 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. Fig. 3.14 excludes Malta for more comprehensive representation purposes. The results of the LMDI analysis show that several factors contribute to the changes in gross electricity generation from RES for the EU-27 countries, as outlined in Table 3.6.

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.

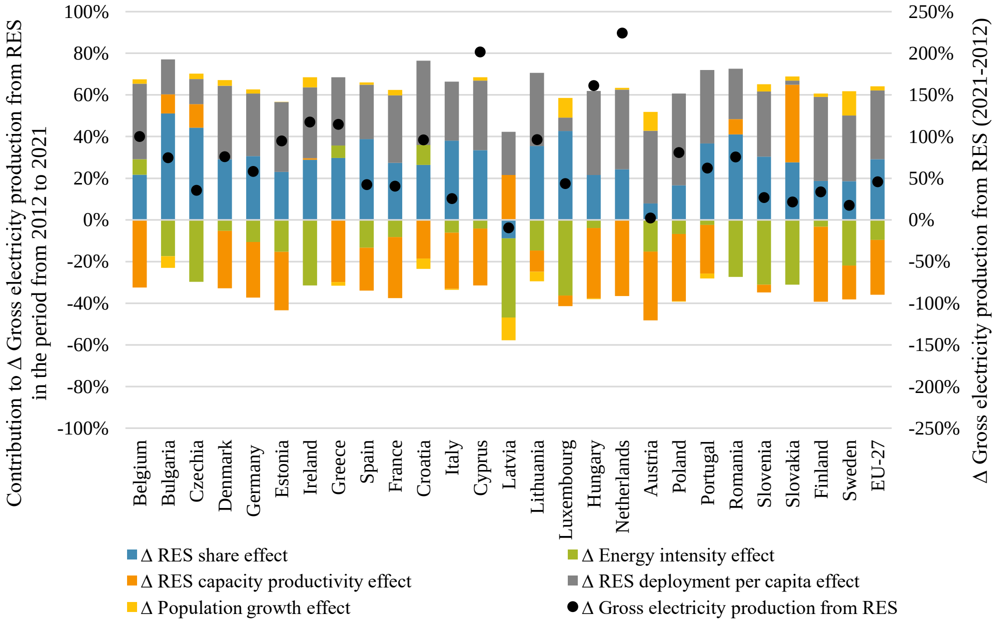


Fig. 3.14. Contribution of LMDI factors to changes in gross electricity production from RES over the period from 2012 to 2021.

Austria showed limited progress in increasing the proportion of gross electricity generation from renewable energy sources when comparing levels in 2012 to those in 2021, with a modest growth of only 2.4%. Similar to Latvia, Austria experienced record-high hydropower production in 2012. In both countries, hydro energy constitutes a significant portion of the overall electricity production mix, making them more exposed to fluctuations in water inflow caused by changes in weather conditions. This observation suggests that countries with lower levels of RES diversification may be more exposed to significant fluctuations in production quantities. Moderate progress in the relative increase of electricity generation from RES was observed for Sweden (17.6%), Slovakia (21.7%), Italy (25.7%), and Slovenia (26.9%). It is noteworthy that Sweden, Austria, and Latvia emerged as prominent nations with a significant share of renewable energy sources in their electricity generation in the year 2021. This discovery suggests that countries that have already achieved a high level of renewable energy sources penetration in their electricity production have experienced slower advancements in the deployment of RES. In contrast, Denmark, Portugal, and Croatia have demonstrated both an initially higher proportion of renewable energy sources in their electricity generation and significant advancements in increasing this share over time.

Table 3.6

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

	Δ RES share effect	**Δ Energy intensity effect**	**Δ RES capacity productivity effect**	**Δ RES deployment per capita effect**	**Δ Population growth effect**	**Δ Gross electricity production from RES**
Belgium	7326	2519	-11005	12275	718	11833
Bulgaria	4271	-1452	771	1392	-467	4515
Czechia	3412	-2289	870	933	201	3126
Denmark	9533	-1719	-9029	11578	897	11259
Germany	105078	-36434	-91404	102899	6840	86978
Estonia	2421	-1609	-2949	3524	15	1402
Ireland	5006	-5456	133	5908	841	6432
Greece	9550	1935	-9609	10519	-540	11856
Spain	46536	-16000	-24791	31357	1287	38389
France	40245	-12168	-43001	47612	3840	36528
Croatia	2595	948	-1824	3981	-495	5205
Italy	28085	-4493	-19887	20857	-333	24228
Cyprus	468	-57	-382	466	23	518
Latvia	-222	-960	544	522	-276	-392
Lithuania	1410	-583	-408	1397	-181	1635
Luxembourg	1480	-1262	-175	227	329	599
Hungary	3877	-690	-6076	7237	-78	4269
Malta	176	-5	-187	221	33	238
Netherlands	25370	-15	-38157	39938	855	27991
Austria	2867	-5515	-11892	12573	3287	1320
Poland	10913	-4419	-21259	28943	-155	14023
Portugal	10596	-689	-6747	10187	-668	12678
Romania	11450	-7629	2055	6750	-1146	11480
Slovenia	1218	-1248	-148	1254	141	1216
Slovakia	924	-1040	1245	65	67	1262
Finland	8400	-1470	-16197	18168	714	9615
Sweden	13661	-16177	-11968	23254	8573	17343
EU-27	356645	-117979	-321478	404033	24323	345544

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. In the EU, total gross electricity generation from RES increased by 45.7% during the period from 2012 to 2021. In total, eleven countries reported a change in gross electricity generation RES below the EU level during this period – Czech Republic (35.5%), Spain (42.4%), France (40.5%), Italy (25.7%), Latvia (-9.5%), Luxembourg (43.7%), Austria (2.4%), Slovenia (26.9%), Slovakia (21.7%), Finland (33.7%), and Sweden (17.6%).

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. The RES capacity productivity effect measures the amount of GDP produced per installed capacity. However, if the installed capacities are currently low and not experiencing significant growth, it indicates untapped potential for renewable energy capacity installations in these countries. It is important to note that RES capacity productivity effect incorporates the speed of economic growth, which in turn also has a direct impact on total electricity demand. If economic growth slows down, this could also indicate a lower total electricity demand and a lower need to generate the amount of electricity required to meet this demand. On the other hand, faster GDP growth has a significant impact on total electricity demand and leads to an increase in electricity generation capacity. A negative RES capacity productivity effect could directly indicate decarbonisation of the electricity sector in countries where economic growth and thus electricity demand tend to be stable or grow only marginally, but the overall sources used for electricity generation are being replaced by renewable energy sources through the gradual abandonment of fossil fuels.

In most countries, population growth had a positive effect and led to an increase in electricity generated on RES, with the exception of 10 countries where the population decreased, such as Bulgaria, Greece, Croatia, Italy, Latvia, Lithuania, Hungary, Poland, Portugal, and Romania. Energy efficiency improvements have reduced energy intensity in most countries and have therefore had a negative impact on the amount of electricity generated by RES. However, in Belgium, Greece, and Croatia, the energy intensity of electricity generation increased during this period, contributing to a positive impact on gross electricity generation from RES. For these countries, the growth in gross electricity generation from RES between 2012 and 2021 was well above the aggregate EU growth rate for this period, while GDP growth was significantly below the average growth rate of all EU member states. This explains the overall increase in the energy intensity effect for these countries, indicating that more electricity was generally generated by RES to produce one unit of GDP. In all countries, RES deployment per capita effect showed an increasing trend and had a positive impact on RES-generated electricity. All EU countries thus show positive progress in the use of renewable energy per population, indicating a trend towards a green energy transition.

In the EU, gross electricity generation from wind power increased by a total of 199 TWh between 2012 and 2021, as outlined in Table 3.7. The largest contributor to the increase in wind power in the EU-27 during this period was the increasing use of wind power per capita. The increasing overall share RES of electricity generation and the effect of the wind share had a positive impact on wind energy generation. The effect of population growth also made a positive contribution, but the effect was less significant than for the other factors. The effect of wind capacity productivity and the effect of energy intensity had a negative impact on gross electricity generation from wind power.

Table 3.7

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

	Δ Wind share effect	**Δ RES share effect**	**Δ Energy intensity effect**	**Δ Wind capacity productivity effect**	**Δ Wind deployment per capita effect**	**Δ Population growth effect**	**Δ Gross electricity production from wind**
Belgium	4432	2545	1459	-7820	8334	289	9238
Bulgaria	-560	751	-253	223	133	-80	213
Czechia	22	184	-120	-52	141	11	186
Denmark	-1962	6757	-1376	-4739	6480	625	5785
Germany	27337	45470	-17139	-49855	54257	2897	62967
Estonia	-193	845	-551	-1289	1484	4	299
Ireland	598	4006	-4421	-612	5508	686	5765
Greece	1620	4208	615	-6044	6424	-191	6633
Spain	-7210	23929	-7568	-7637	10402	674	12589
France	13004	9760	-2865	-20237	21142	850	21653
Croatia	1158	199	121	-1445	1767	-67	1733
Italy	4023	3961	-580	-5452	5712	-144	7520
Cyprus	-185	227	-26	31	4	9	61
Latvia	31	5	-38	-4	45	-11	27
Lithuania	195	442	-140	-544	939	-69	822
Luxembourg	191	89	-80	-68	72	33	237
Hungary	-760	637	-175	193	13	-14	-106
Malta	0	0	0	0	0	0	0
Netherlands	-1062	12674	50	-10834	11755	440	13023
Austria	3997	178	-274	-3649	3712	314	4277
Poland	4732	5198	-2330	-5559	9522	-77	11487
Portugal	-2569	4700	-301	-1364	2767	-278	2956
Romania	1536	2492	-2038	136	2100	-291	3936
Slovenia	5	1	-1	-1	2	0	6
Slovakia	-1	0	0	2	-2	0	-1
Finland	6270	1348	-17	-6716	7058	69	8012
Sweden	15321	3349	-2116	-17090	19132	1483	20080
EU-27	69968	133955	-40165	-150426	178904	7161	199398

Slovenia, Latvia, and Cyprus have experienced low progress in wind-generated electricity, with an increase of 6 GWh, 27 GWh, and 61 GWh, respectively. 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 renewable energy share in electricity production, have shown proactive efforts in increasing their wind and solar PV capacities. Instead of following a similar path, 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. The results presented in this study align with the research conducted by [137], which emphasised Latvia's historical involvement in bioenergy and hydropower development. However, this overemphasis on incumbent technologies might potentially hinder future RES growth.

Table 3.8 shows the LMDI results for the changes in gross electricity generation from solar PV over the period. Across the EU-27, an increase in gross electricity generation from PV was observed from 2012 to 2021. In the EU-27, total gross electricity generation from solar PV increased by 92 TWh. The largest contributors to the changes in electricity generated by PV were the increase in per capita use of PV, solar PV share effect, and RES share effect. Population growth also made a positive contribution. While PV capacity productivity and the energy intensity effect had a negative impact on the changes in gross electricity generation from solar PV.

Table 3.8

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

	Δ Solar PV share effect	**Δ RES share effect**	**Δ Energy intensity effect**	**Δ Solar PV capacity productivity effect**	**Δ Solar PV deployment per capita effect**	**Δ Population growth effect**	**Δ Gross electricity production from PV**
Belgium	1053	1448	540	-2692	2973	148	3470
Bulgaria	-13	668	-238	-154	503	-78	688
Czechia	-500	733	-481	177	197	42	167
Denmark	772	360	-62	-936	1038	34	1205
Germany	6386	19771	-6860	-19291	21630	1324	22960
Estonia	309	50	-31	-338	363	1	354
Ireland	88	2	-16	-79	94	2	92
Greece	750	2132	591	-3549	3771	-139	3557
Spain	9344	4792	-1081	-12329	12851	152	13729
France	8259	3382	-1093	-10646	11092	309	11305
Croatia	121	6	2	-113	134	-4	147
Italy	1433	5423	-881	-6525	6840	-114	6177
Cyprus	236	184	-25	-374	414	11	447
Latvia	7	1	-1	-7	7	0	7
Lithuania	155	29	-18	-162	189	-4	189
Luxembourg	103	78	-64	-134	138	20	142
Hungary	2494	1084	-8	-2918	3153	-16	3788
Malta	19	161	-2	-181	212	31	239
Netherlands	5102	5820	-81	-10659	10967	155	11305
Austria	2405	35	-94	-2347	2375	70	2445
Poland	3522	106	96	-3515	3734	-9	3933
Portugal	1488	414	-151	-2054	2162	-15	1845
Romania	1465	315	-579	-418	985	-72	1695
Slovenia	244	55	-79	-269	331	8	290
Slovakia	142	75	-88	93	20	6	247
Finland	252	28	4	-266	272	1	292
Sweden	1325	124	-27	-1406	1462	29	1507
EU-27	46963	47274	-10725	-81093	87910	1893	92222

In absolute terms, Germany (22.9 TWh), Spain (13.7 TWh), France (11.3 TWh), and the Netherlands (11.3 TWh) achieved the largest growth in gross electricity generation from solar PV between 2012 and 2021. In contrast, Latvia (6.8 GWh) and Ireland (92.3 GWh) recorded the slowest progress.

The LMDI results indicated that the impact of the RES share effect was more noticeable in wind-generated electricity when compared to the LMDI results for solar PV. This phenomenon may be attributed to the fact that wind energy exhibits greater capacity and production capabilities in generating electricity in comparison to solar PV systems. This implies that boosting the overall share of RES has a more substantial impact on the amount of electricity generated from wind. In general, the aggregated results of the EU-27 showed that an increasing overall share of renewable energy resources positively influences the overall deployment of wind and solar energy in electricity generation.

3.3.3. LMDI decomposition analysis of energy imports

LMDI decomposition analysis was used to examine the changes in net energy imports in the EU-27 during the period from 1995 to 2020 divided into five groups of five-year periods. The change in net energy imports was measured by four main factors: changes in energy dependence, changes in energy intensity, changes in economic growth, and population. The results showed that not only has no progress been made in reducing the EU's energy import dependency, but the situation has actually worsened and become more unstable over the past five years. The results showed different energy structures and energy import tendencies for the countries. Fig. 3.15. illustrates the results of the LMDI decomposition analysis for the EU-27 for the period 1995 to 2020.

The results showed that economic growth and population growth were the main drivers of total energy demand growth, which in turn increases the need for net energy imports in the EU. The EU's energy import dependency has fluctuated over the periods. In the first two periods (1995-2000 and 2000-2005), there was an upward trend in energy import dependence, which was reflected in annual increases and greater EU exposure to energy trade. In the third period (2005-2010), the EU's overall energy import dependency showed slightly decreasing trend, which was mainly due to the global financial crisis, which reduced energy demand in all EU countries. In the fourth period (2010 - 2015), the EU's dependence on energy imports increased only minimally compared to growth in 1995-2005 due to implemented climate action plans, which put pressure on EU countries to increase the share of renewable energy in total energy consumption.

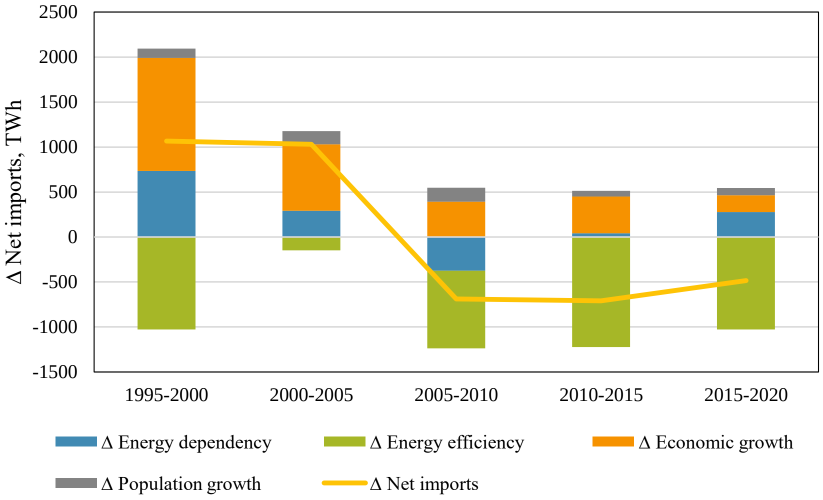


Fig. 3.15. LMDI decomposition analysis results for EU-27.

More detailed analysis is performed for the period of the last five years (2015-2020) for all 27 EU countries to examine the recent situation in accelerating energy independence at the EU level. In the fifth, the most recent period (2015-2020), the EU showed rising energy import dependency that have reached the highest value compared to other periods. The growing dependence on energy imports is explained by the stable energy demand in the EU, where the growing economy and population demand fossil fuels, which are mainly consumed in transport, industry, households and agriculture. However, due to the EU's strategic climate change policies, the EU has significantly reduced its domestically generated fossil energy during 2015-2020. Therefore, to balance the energy demand, the required fossil energy was imported from abroad, mainly from Russia [138]. This has in turn pushed net energy imports during 2015-2020 to increase.

The importance of energy efficiency measures was also highlighted in the results of the LMDI decomposition analysis, as energy efficiency was the most important counter-response factor that decreased the need for net energy imports in all periods studied. The greatest impact of energy efficiency improvements was in the period from 2010 to 2015. Fig. 3.16. illustrates the contribution of the LMDI decomposition analysis factors to the changes in EU-27 net energy imports for the fifth study period (2015-2020), as well as the percentage change in total net energy imports over this period. Moreover, Table 3.9 summarizes the results for each country.

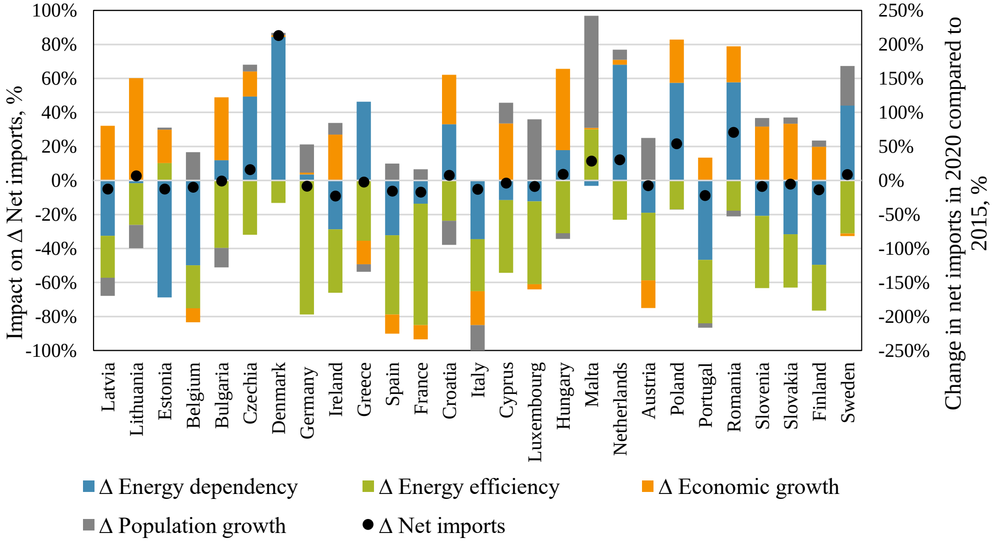


Fig. 3.16. Contribution of LMDI decomposition analysis factors to ΔNet imports for EU-27 in the period from 2015 to 2020.

The results showed 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.

In absolute terms, the countries with the highest net energy imports are Germany, Italy, France, Spain, the Netherlands, Poland, and Belgium, so changes in energy import dependency in these countries strongly influence the overall degree of energy independence of the EU.

The supply of natural gas and petroleum products is the main cornerstone for strengthening energy independence in almost all countries of the European Union [139]. 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 [140], [141]. 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 [103].

Table 3.9

LMDI Energy Imports Decomposition Analysis Results from 2015 to 2020 for EU-27 (GWh)

Country code	**Δ Energy dependency**	**Δ Energy efficiency**	**Δ Economic growth**	**Δ Population growth**	**Δ Net imports**
LV	-3118	-2364	3083	-1021	-12.4%
LT	-361	-5281	12969	-2954	6.9%
EE	-1528	227	435	29	-12.5%
BE	-42974	-21831	-7039	14352	-9.9%
BG	3039	-10179	9478	-2927	-0.7%
CZ	34172	-22102	10179	2722	15.9%
DK	66920	-10445	786	1138	213.3%
DE	11952	-268706	3621	56584	-8.5%
IE	-30082	-39021	28206	7211	-22.7%
EL	29602	-22685	-8873	-2792	-2.2%
ES	-68306	-98778	-24019	20981	-15.4%
FR	-37083	-194658	-22623	17988	-16.9%
HR	4944	-3555	4358	-2126	7.5%
IT	-62686	-55787	-36252	-26973	-12.9%
CY	-1379	-5130	4015	1451	-3.6%
LU	-1749	-6908	-435	5088	-8.6%
HU	8183	-14197	21899	-1560	9.1%
MT	-252	2392	81	5253	28.8%
NL	196205	-66484	8525	17231	30.6%
AT	-6903	-14540	-5926	9094	-7.7%
PL	157877	-46741	69516	-502	54.0%
PT	-30285	-24141	8663	-1696	-22.1%
RO	43875	-13515	16048	-2565	70.8%
SI	-2615	-5338	3979	634	-8.9%
SK	-7254	-7196	7668	836	-5.2%
FI	-23580	-12829	9388	1739	-13.8%
SE	19555	-13858	-682	10370	9.0%
EU-27	**256172**	**-983649**	**117047**	**127589**	**-5.0%**

In order to show the positions of each EU-27 country in terms of level of energy import dependency and the share of renewable energy sources in total energy consumption, a correlation analysis was performed. Fig. 3.17. illustrates the relationship between the share of renewables in gross final energy consumption and energy import dependency in 2020 for all EU-27 countries.

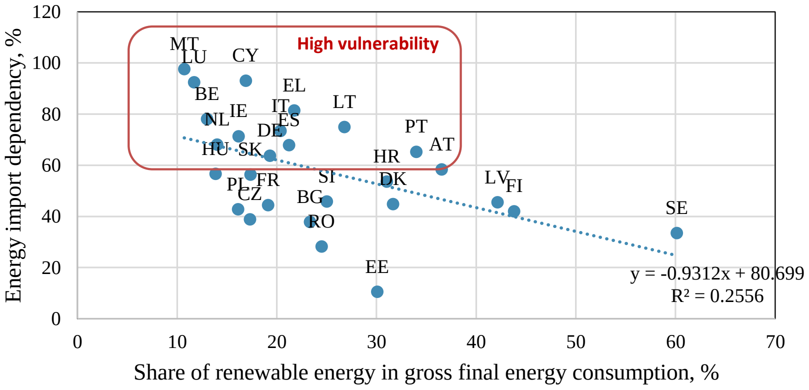


Fig. 3.17. Relationship between the share of renewable energy in gross final energy consumption and energy import dependency in 2020 for EU-27 countries.

The results showed 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.

Increasing energy self-sufficiency can be achieved not only through energy efficiency measures, but also by building the necessary infrastructure and enabling environment for domestic energy production. The development of sufficient infrastructure to exploit the maximum potential of renewable energy, which includes RES production, distribution and accumulation technologies, is extremely important for all EU countries [142]. RES contributes to the EU's two main strategic development priorities. First, RES is the key element for the decarbonization of the energy system and contributes to the achievement of climate change mitigation goals. Second, it strengthens national energy security by making it possible to become less dependent on external energy resources sourced through massive energy imports [142]. The greatest advantage of RES is that it is not limited to one energy carrier that is a depleting resource, but offers a wide variety of energy sources such as wind, solar, biomass, geothermal, and hydro. Therefore, depending on the geographical and climatic conditions, it is possible for each country to develop RES infrastructure for the higher production of a specific type of RES [142].

3.4. Municipal energy system

Further assessment involved analyzing local energy systems from the perspective of municipalities. First, a municipal energy transition index was developed to evaluate the readiness of municipalities for adopting smart energy system solutions and advancing their energy transition efforts. Next, a case study of Gulbene municipality was conducted to compare various energy storage technologies and assess their potential integration into the municipal energy system. Finally, the mental models of different municipal energy system stakeholders were examined to capture diverse perspectives and social challenges associated with local energy transitions.

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. The aggregated municipal energy transition index results and benchmarks are then discussed.

Fig. 3.18. 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 inhabitants, 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 municipality) to 0.28, the lowest (for Tukums municipality), with an average benchmark value of 0.46.

The main cornerstone of the Tukums municipality is the low share of public building renovation and building heat consumption efficiency. Similarly, the Taurage municipality had the lowest share of renovated public buildings and the highest average heat consumption of public buildings. However, the Taurage municipality had the lowest municipal electricity consumption per inhabitant, indicating a higher power consumption efficiency compared to other municipalities. In contrast, the lowest power consumption efficiency was observed in Tomelilla municipality. Although the overall share of renovated public buildings in Tomelilla municipality was considerably high (63%), the overall average heat consumption of municipal buildings was the third highest (126 kWh/m2). This could be potentially explained by the colder climate. Although the Wejherowo municipality had the highest municipal building renovation share and lowest average heat consumption, its main challenge is the considerably high electricity consumption of the municipal infrastructure. This could potentially be explained by inefficient public street lighting in the municipal region, indicating opportunities for the replacement of public street lighting. Similarly, the electricity consumption per inhabitant of the Gulbene municipality could be improved. Municipal infrastructure includes municipal buildings and equipment, public street lighting, water supply, sewerage, and other.

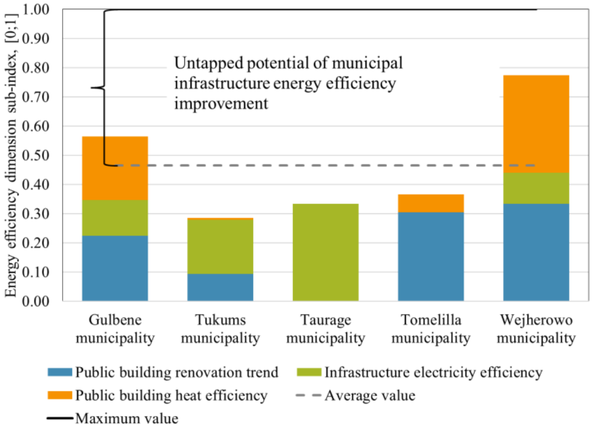


Fig. 3.18. Energy efficiency dimension sub-index results.

Fig. 3.19. 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 per inhabitants, MW/inhabitants), RES heat share (share of produced heat energy from renewable energy resources, %), and transport decarbonization (share of electrical and alternative fuel transportation in the municipal transport system, %). Energy decarbonization dimension sub-index values indicated the highest range in the achieved results for the municipalities, with highest value of 0.92 (for Tomelilla municipality) and lowest of 0.08 (for Wejherowo municipality).

The Tomelilla municipality indicated the highest level of decarbonization in the power, heat, and transport sectors, and therefore reached the highest energy decarbonization sub-index score. There are 35.9 MW installed RES power plants in the municipal region with 29 MW wind turbines and 6.9 MW solar PVs. The heat production in both regions' district heating and individual heating of municipal buildings is entirely based on biomass (wood pellets and chips) and electricity (heat pumps). Moreover, Tomelilla municipality stands out with a high share of transport sector decarbonization. Besides diesel and petrol, municipal transport consumes considerably high amounts of biogas (27.5 thousand kg), HVO (36.8 thousand liters), and electricity (2.5 MWh) for transportation needs. Moreover, according to Tomelilla municipal representatives, the local public transport company entirely uses RME (biodiesel) for their bus fleet, and the public transport fleet is entirely based on renewable energy.

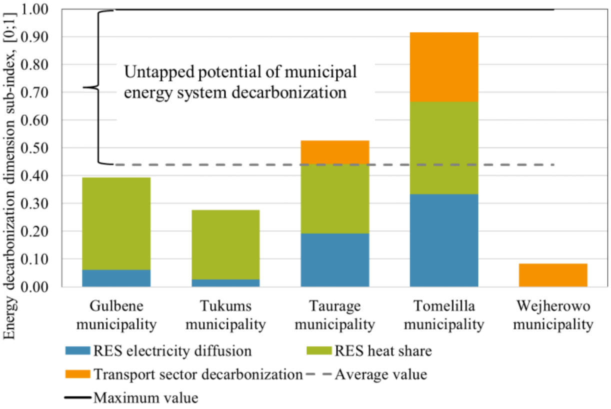


Fig. 3.19. Energy decarbonization dimension sub-index results.

Decarbonization of the transport sector is the main challenge for all municipalities. Besides the Tomelilla municipality, noticeable transport decarbonization efforts are observed in the Taurage and Wejherowo municipalities. In the Taurage municipality, there has been a significant increase in the electricity consumption of municipal private transport (146 MWh in 2022) and public transport (16 electrical buses with a total consumption of 146 MWh in 2022). Similarly, the Wejherowo municipality consumed 230 MWh of electricity to meet public transport needs. Moreover, the Wejherowo municipality considers the purchase of hydrogen buses that can be used for public transport fleets in the future. However, regarding renewable energy deployment for heat and power generation, the Wejherowo municipality showed the poorest results. According to municipality representatives and municipal energy data, no RES power plants are installed in the municipality. Power is produced by the natural gas CHP. In the municipal region, there are only small photovoltaic installations (micro-installations) with a capacity of 4-5 kW, which are individual sources installed in private buildings (mainly single-family residential houses). The heat in district heating in the Wejherowo municipality is produced entirely by fossil fuels, such as coal and natural gas. Furthermore, the results of the energy decarbonization sub-index show that Wejherowo, Tukums and Gulbene municipalities significantly lag behind in installation of RES power plants such as solar PVs and wind turbines in the municipal region. Although both Latvian municipalities possess a considerably high share of RES in heat generation, which is mostly based on biomass utilization, significantly lower amounts of RES power plant installation were observed in the municipalities compared to the other Baltic Sea Region municipalities selected for the analysis.

Fig. 3.20. 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 lowest with 0.25 for Tukums, Taurage and Tomelilla municipalities.

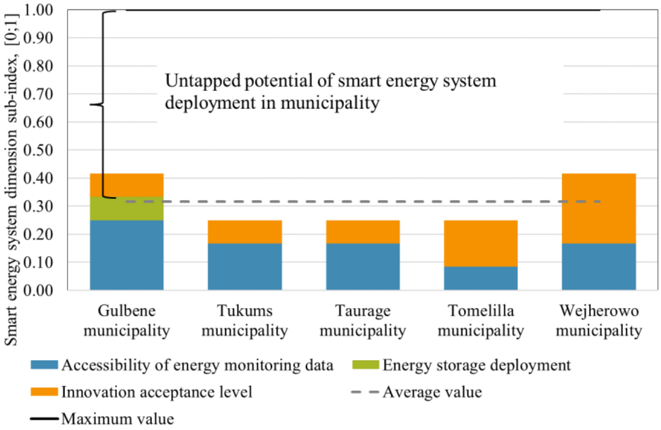


Fig. 3.20. Smart energy system dimension sub-index results.

The Gulbene municipality stood out as the only municipality that has installed renewable energy storage technologies. There is one small battery system with a total capacity of 9 kWh installed on Gulbene’s municipal building, in combination with PV panels. There are also small units of thermal energy storages in individual boiler houses. The Gulbene municipality also demonstrated considerably good data quality and solutions for necessary data acquisition. Regarding innovation acceptance in terms of possible hydrogen, biomethane, and synthetic fuel integration, Gulbene municipality was reluctant. According to the municipal representatives, the Gulbene municipality does not plan to implement hydrogen systems currently because there is no further infrastructure to use hydrogen in the Gulbene region, and it is still expensive and unexplored.

A similar reluctance was also observed by the representatives of Tukums and Taurage municipalities, which do not plan specific actions with regard to hydrogen research and possible integration in municipal infrastructure. However, more positive attitudes and concrete considerations were expressed by the Tomelilla and Wejherowo municipalities with regard to innovation deployment, such as hydrogen and its derivative integration into municipal energy systems. Tomelilla is interested in exploring the long-term potential of hydrogen in the municipality. Most concrete actions were demonstrated by the Wejherowo municipality, where municipal public transport company plans to switch urban transport to buses powered by hydrogen fuel (the first hydrogen bus has already been tested practically in the city for a period of two weeks in December 2023). By 2035, it is planned to purchase 27 zero-emission buses powered by hydrogen fuel. To become completely independent from external hydrogen supplies, investment in the construction of its own hydrogen production and refueling station in the municipality is also planned.

This research marked that data collection and quality issue is still one of the major challenges and cornerstones of municipalities, which is also reflected in the values of the digitalization and energy monitoring data accessibility indicator (i7). According to observations, there is no single digital energy monitoring system that covers all economic sectors implemented in municipalities. All selected municipalities encountered significant challenges in data collection. A lack of data monitored directly by the municipality has been observed in several forms. First, data on electricity consumption and production are available only to the national system operator with no direct access to the municipality without special requests, which often involves unnecessary bureaucratic procedures. This issue was observed in the Gulbene, Tukums, and Wejherowo municipalities. Second, district heating and public transport companies are reluctant to provide data that often result in inconsistent and incomplete heat consumption assessments of all sectors of the municipal region. Third, some data are monitored by national authorities and are classified, meaning that municipalities do not have access to these data. This was most prominently observed in the Tomelilla municipality. No direct control over energy data significantly hinders municipal efforts in energy transition.

Table 3.10 outlines the aggregated results of the ETI and benchmarking values for all three sub-dimensions. Fig. 3.21. illustrates the aggregated results for municipal energy transition index (ETI) of the selected municipalities. The index results illustrate the contribution of each dimension – energy efficiency, energy decarbonization, and smart energy systems. The results show which of the dimensions for a specific municipality is of particular challenge at the moment, and which is the strongest compared to other municipalities.

All municipalities show major untapped potential for sustainable municipal energy transition given that the maximum index value is equal to 1. The aggregated results reveal that for Gulbene municipality key strengths are 100% renewable heat generation system and experience in energy storage technology deployment, i.e. installation of the first battery storage system. However, challenges persist, such as slow progress in transport decarbonization, limited deployment of RES power plants like solar panels and wind turbines, and comparatively high electricity consumption in municipal infrastructure. For Gulbene municipality the identified opportunities and untapped potentials lie in include enhancing energy efficiency further, increasing the installation of RES power plants, electrifying the heat sector through the integration of heat pumps and energy storage systems, and advancing transport sector decarbonization efforts.

Table 3.10

Benchmarking Results of the Composite Municipal Energy Transition Index (*ETI*)

	Avg	**Gulbene municipality**	**Tukums municipality**	**Taurage municipality**	**Tomelilla municipality**	**Wejherowo municipality**
Public building renovation trend		0.22	0.09	0.00	0.30	0.33
Infrastructure electricity efficiency		0.12	0.19	0.33	0.00	0.11
Public building heat efficiency		0.22	0.01	0.00	0.06	0.33
Energy efficiency sub-index	**0.46**	**0.56**	**0.28**	**0.33**	**0.37**	**0.77**
RES electricity diffusion		0.06	0.03	0.19	0.33	0.00
RES heat share		0.33	0.25	0.25	0.33	0.00
Transport sector decarbonization		0.00	0.00	0.08	0.17	0.08
Decarbonization sub-index	**0.44**	**0.39**	**0.28**	**0.53**	**0.92**	**0.08**
Accessibility of energy data		0.25	0.17	0.17	0.08	0.17
Energy storage deployment		0.08	0.00	0.00	0.00	0.00
Innovation acceptance level		0.08	0.08	0.08	0.17	0.25
Smart energy sub-index	**0.32**	**0.42**	**0.25**	**0.25**	**0.25**	**0.42**
Municipal energy transition index	**0.41**	**0.46**	**0.27**	**0.37**	**0.51**	**0.42**

For Tukums municipality key strengths lie in the good efforts of heat sector decarbonization and successfully established energy management system. However, the key weaknesses are the low public building renovation rate and the unused potential of RES power plant installation (solar PV and wind power). Key opportunities for Tukums municipality energy transition would be the acceleration of higher RES deployment in power production and transport decarbonization, improvements in infrastructure, and building energy efficiency.

Favorable conditions for wind energy installations, which have led to a greater number of renewable energy source power installations than in other municipalities, and minimal electricity consumption of municipal infrastructure are two of Taurage municipality's greatest strengths. Low rates of public building renovation and transportation decarbonization progress are significant obstacles. Key opportunities for the Taurage municipality include the potential to produce hydrogen and synthetic fuel from surplus wind energy, improving the energy efficiency of public buildings and decarbonizing transport.

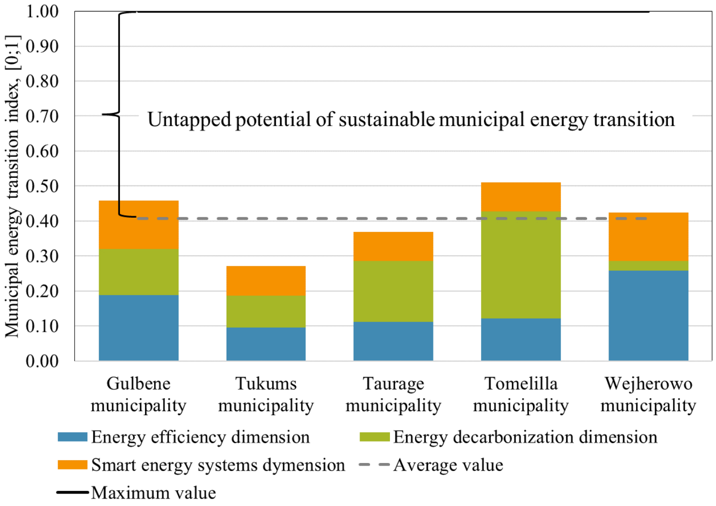


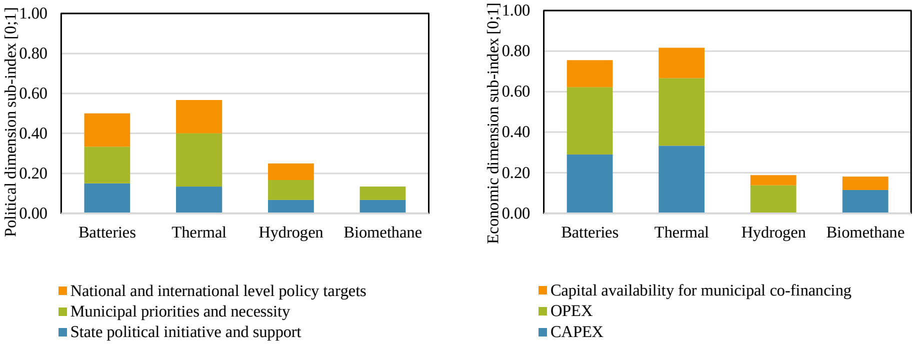
Fig. 3.21. Municipal energy transition index (*ETI*) results.

The strengths of the Tomelilla municipality are its 100% renewable heat generation system, its substantial use of biofuels in the transportation sector, its positive trend in the installation of RES power plants, and its positive trend in the renovation of public buildings. The public building's substantial electricity consumption and the complex nature of energy management and monitoring constitute major weaknesses. Key opportunities include the electrification of the heat sector, the inclusion of storage systems to increase self-sufficiency, and the substantial potential for hydrogen production from excess renewable energy.

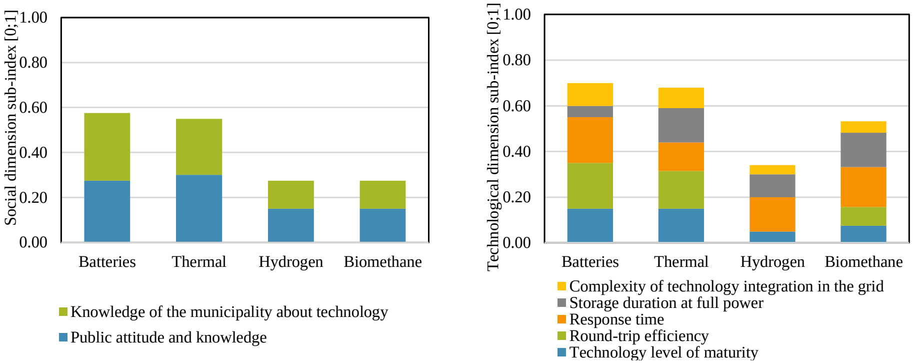
For the Wejherowo municipality, the main strengths are the good trend in the renovation rate of public buildings, the considerably low average heat consumption of public buildings and the good efforts in the decarbonisation of public transport. The main weaknesses are the heat generation based entirely on fossil fuels, the lack of municipal measures in the installation of RES power plants (PV panels, wind turbines) and the inefficient electricity consumption of public street lighting. The main opportunities are the utilisation of the untapped RE electricity potential and possible hydrogen production, the massive possibilities of decarbonising and electrifying the heat sector and improving the efficiency of public street lighting.

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

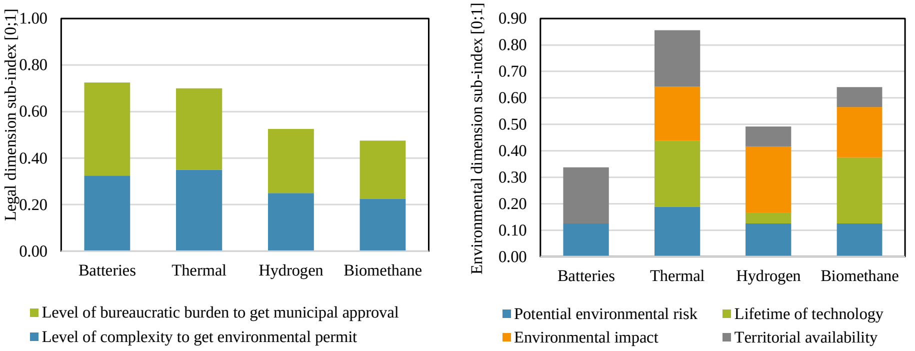
Nineteen indicators grouped into six main dimensions such as political, economic, social, technological, legal, and environmental were used to evaluate and compare the selected renewable energy storage alternatives in a municipal context. The results first represent the values of the subindices of the dimensions (see Fig. 3.22). Then, the results of the sub-indices were combined into PESTLE composite index which is illustrated in Fig. 3.23. The results of the individual dimensions are explained in detail below, followed by the analysis of the combined results of the PESTLE composite index.



(a) Political dimension sub-index **(b) Economic dimension sub-index**



(c) Social dimension sub-index **(d) Technological dimension sub-index**



(e) Legal dimension sub-index **(f) Environmental dimension sub-index**

Fig. 3.22. Sub-indices of PESTLE dimensions.

Political dimension sub-index results show that thermal energy storage outperforms the other technologies, followed closely by batteries. Thermal storage scores much higher due to direct municipal priorities and the need to store thermal energy. Since municipalities have less control over the electricity system, they do not feel the benefits of batteries as strongly as those of thermal storage.

There is no strong support from municipality representatives towards the potential use of hydrogen and biomethane because the main heat source in the municipality is biomass, not natural gas. In addition, municipality representatives acknowledge that there are currently more government initiatives and support for the integration of thermal energy storage and batteries. There are no strong national policies and regulations focused on supporting and accelerating the development of biomethane and hydrogen storage infrastructure, which is reflected in the results of the political dimension sub-index. At the international level, batteries have stronger policy targets in the EU to support rapid deployment, while thermal energy storage is given less priority compared to batteries. For thermal energy storage, priorities depend more on national governments and their visions. Hydrogen deployment is also highly prioritized at the EU level, while biomethane is less frequently prioritized and there is no strong and focused policy vision.

The results of the economic dimension sub-index show that thermal energy storage and batteries for electricity storage are currently the most cost-effective solutions compared to biomethane and hydrogen. Both initial specific capital investment (EUR/kW) and operation and maintenance costs (EUR/kWh) for thermal energy storage and batteries are significantly lower than for hydrogen and biomethane, which require high investments in infrastructure development and integration into existing energy systems. The capital availability of municipal co-funding for batteries and thermal energy storage solutions is significantly higher due to lower specific investment costs and a reasonable payback period that justifies the economic viability of the technology.

The results of social dimension sub-index show that both overall public attitude and knowledge and knowledge of the municipality representatives about technology is considerably higher for batteries and thermal energy storage than for hydrogen and biomethane. This is due to the fact that municipalities are generally more familiar with these technologies, as small-scale energy storage solutions for electricity and thermal energy are already installed in the region. Municipal representatives acknowledge that there is still much that is unknown about the optimal performance of these technologies and understanding of their benefits, but as they gain experience, they will become more proficient in their understanding and utilize these technologies. On the other hand, hydrogen and biomethane technologies are less understood and municipality representatives have very limited knowledge about these new emerging technologies. Due to the lack of knowledge, the municipality representatives are skeptical about these solutions, as there are no real examples of best practices in other Latvian municipalities yet, and no basis and certainty has been established for the potential benefits of these solutions.

In general, public attitudes and knowledge about batteries and thermal energy storage tend to be positive, especially now that electricity prices have risen extremely, and the importance of energy self-sufficiency has been elevated nationally due to the global geopolitical situation. In general, people base their overall attitude on familiarity with technology. There are several small-scale thermal energy storage solutions installed in the municipal boiler houses, and people have a positive attitude toward it because they understand the benefits. Public understanding and acceptance of solar batteries has grown recently because of the examples already installed in the region, which are used to justify the investment and explain the benefits to the general public. However, for hydrogen and biomethane, attitudes tend to be negative due to a lack of understanding of these technologies and people simply not seeing how and where these energy sources can be used. These technologies are seen as very new to the public, and there is much that is unknown and no information that easily explains the benefits of these technologies to the general public.

Compared to the other PESTLE sub-indices, the technological dimension sub-index contains a larger number of indicators describing the main factors of technological performance. The results of the technological dimension sub-index show that batteries and thermal energy storage technologies outperformed biomethane and hydrogen storage in the technological dimension sub-index.

This is mainly due to the higher maturity of the technology and the lower complexity of the technology to be integrated into the existing grid for batteries and thermal storage. This means that these technologies are more mature and already commercialized, which significantly increases the overall confidence in these technologies, as their performance has already been proven. However, the opposite is true for hydrogen and biomethane storage: these technologies are mostly still in the research and demonstration phase, and there are few already commercialized and proven solutions. Hydrogen and biomethane storage also require extensive modifications and adaptations to the existing infrastructure to integrate these energy resources into the existing grid, while the integration of batteries and thermal energy storage is much simpler and does not require much additional effort to adapt the grid.

In general, batteries and thermal storage also have higher round-trip efficiency compared to other alternatives. Round-trip efficiency is critical to a sustainable energy system because it represents the fraction of electricity that is stored and later retrieved, characterizing the extent of energy loss in storage [143]. Hydrogen and biomethane have significantly lower round-trip efficiencies, which negatively impacts the overall energy efficiency of the conversion process and the sustainable use of these energy resources. Response time is another important indicator that characterizes energy storage technologies. Response time is the time required for the entire energy system to provide energy at its full capacity [144]. Batteries show the fastest response time (ms) compared to other technologies where response time ranges from seconds to minutes for hydrogen, biomethane and thermal energy storage technologies. The results of technology sub-index show that the main disadvantage of batteries is the shorter duration of storage at full power compared to other alternatives.

The legal dimension sub-index represents the degree of legal and administrative burden associated with the municipal energy system development project. A higher level of bureaucratic burden increases the time for approval of energy development projects and could therefore lead to significant delays in the transition to a sustainable energy system. The results show that both the bureaucratic burden of obtaining a municipal approval and the complexity to get environmental permit is lower for batteries and thermal energy storage than for hydrogen and biomethane. Due to the significantly higher uncertainty of hydrogen and biomethane, it would be much more complicated to obtain environmental permits to demonstrate that all safety concerns have been addressed and environmental risks have been eliminated. Similarly, because of the higher initial capital investment for hydrogen and biomethane, it would be much more difficult to convince municipality representatives to support these development directions unless reasonable economic justifications are presented.

The results of the environmental dimension sub-index showed that batteries had the lowest value among all technologies, with a value of 0.34. This is due to the shorter lifetime of the technology and the higher environmental impact. In general, lifetime of lithium-ion batteries ranges from 10 to 20 years [67]. Although the average lifetime of batteries is increasing annually due to technological advances, it is still lower on average than other technologies in this study [145].

Considering the entire life cycle of technologies, which includes material extraction, manufacturing, and disposal of the product, batteries were found to have the greatest environmental impact among alternative technologies. The extraction of lithium-ion resources is a highly energy-intensive process that significantly impacts the overall resource efficiency of lithium-ion battery production [146]. In addition, the short life of batteries requires much more frequent replacement of battery components, resulting in higher environmental impacts [73]. There are still many concerns about the sustainable disposal of lithium-ion batteries, as leaks of hazardous substances can occur [146].

Potential risks and damages are also associated with hydrogen and biomethane storage, mainly due to the safety risks of the respective technologies. For biomethane, the risk of methane leakage should be considered. The production and transportation of biomethane poses a risk of methane leakage, a potent greenhouse gas. This can occur from biogas plants, pipelines, and storage tanks [147]. Strict safety requirements must be observed for hydrogen, as hydrogen is a highly flammable gas. In addition, the production of hydrogen requires water, which can pollute local water resources if not handled properly [148]. Thermal energy storage is generally associated with lower environmental risks and potential damage.

According to municipality representatives, there is space and areas in the region for the installation of all the energy storage technologies of this study, although it would be much easier to find suitable areas for batteries and thermal energy storage than for hydrogen and biomethane energy storage, which require more specific conditions. For hydrogen, closeness and availability of RES such as wind and solar power to generate electricity for electrolysis is required, and close access to water resources is recommended. For biomethane, closeness to existing biogas plants and availability of resources for biogas production in the region, such as organic waste, crop residues, animal manure, and others, are required. In addition, proximity and access to existing natural gas infrastructure for potential injection into the gas grid and closeness to water resources to be used in bioreactors are highly recommended for biomethane storage technologies. In terms of technology-specific requirements for specific geographic conditions, less stringent requirements are needed for batteries and thermal energy storage than for power-to-gas and power-to-liquid technologies. For batteries, close access to the power grid and availability of space are required. For thermal energy storage, closeness to the heat source, availability of space and, depending on the storage type, availability of water is required.

Fig. 3.23 illustrates the overall PESTLE composite index results. 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.

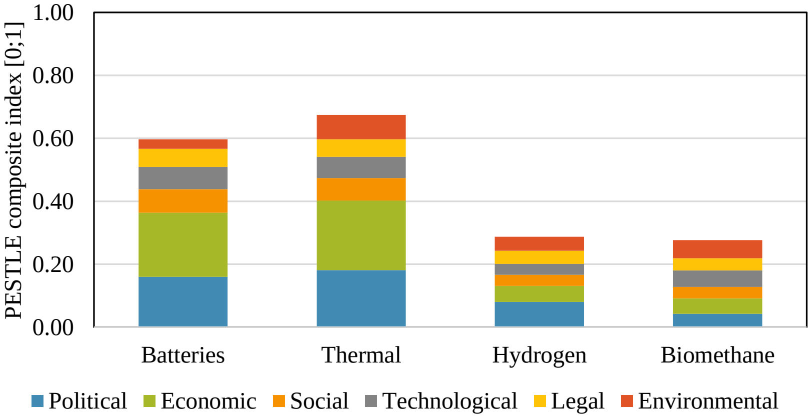


Fig. 3.23. PESTLE composite index results.

The political and economic dimensions had the strongest influence on the overall results of the composite index, as the weights assessed by the municipality representatives were higher in the index calculation (for the political dimension - 0.32 and the economic - 0.27). As a result, thermal energy storage outperformed the other alternatives, mainly due to its stronger position in the political and economic dimension sub-index. In the case of batteries, the environmental dimension proved to be the weakest position due to the higher environmental impact it causes. However, it did not have a major impact on the overall results of the composite index, as it had an overall weight of 0.09. At the dimension level the highest disparities in the sub-index results were noticed in the economic and environmental dimensions.

Similar results of the PESTLE composite index were obtained for hydrogen and biomethane, as both technologies were found to have similar limiting factors for technology deployment in the municipal context. High capital investment, less targeted policy initiatives and support, and the higher complexity of these technologies to integrate into the existing grid are among the main reasons why they lag significantly behind battery and thermal energy storage development.

Results from the interviews with municipality representatives

Municipality representatives highlight that national energy priorities currently outweigh local energy community efforts, despite the latter being more efficient. Municipalities have limited control over the electricity grid, unlike heat generation,, which remains managed more at the local level.

To accelerate the regional transition to low-carbon energy systems and make it more cost-effective, it would be beneficial to establish a centralized team of professionals to manage environmental projects, rather than each municipality figuring it out on its own. Currently, one of the biggest cornerstones of the green energy transition is the lack of knowledgeable individuals and professionals to oversee such development projects, which include the development of energy storage infrastructure. It would be more efficient to have a national, centralized program that coordinates green energy transition projects in municipalities with a team of experts to drive these ambitious development projects. Collaboration and knowledge exchange between municipalities would improve in this way, and the process of deploying energy storage in the regions would accelerate significantly.

Knowledge of batteries is higher in municipality than other technologies, as 10 kW batteries are already installed in the municipality building and integrated into the overall solar power system of the building. Although the cost of batteries has decreased somewhat, they are still quite expensive relative to their benefits. These batteries can store about 1 hour of electricity, but in terms of cost, the batteries represent one-third of the total initial capital investment for the solar power plant. In winter, when solar power is not available to charge the battery, the plant draws power from the grid.

Hydrogen knowledge is low, though municipalities acknowledge its future potential, particularly in public transportation. However, most municipalities are cautious, awaiting further technological advancements. Since this municipality does not use natural gas for heating, biomethane infrastructure development is not currently considered.

The municipality in this case study uses biomass for heat generation, so the overall share of renewable energy sources in the municipality is considerably high. Most of the government funding available for green energy transition in municipalities is based on the principle of CO_2 emission reduction, meaning that if a new development project can achieve higher CO_2 emission reduction, the higher chance for that municipality is to receive government funding. If a municipality is already highly decarbonized, it is very difficult to obtain funding. And if a municipality cannot demonstrate high CO_2

reduction potential, then the opportunities to obtain government funding are very limited, and a project without government funding is no longer economically viable for the municipality because the payback period is unreasonably long. Therefore, municipality representatives acknowledge that there is very limited ability for municipality to fund such investment projects as investments in energy storage technologies since municipality alone cannot bear the high investment costs.

Municipality representatives mention that there are psychological barriers, such as lack of knowledge about available technologies and their benefits. If the technology is unknown, then the municipality tend not to choose it because they need to be able to operate with it and understand in detail how the system works. Lack of knowledge also impacts decision making regarding possible future directions in the municipality. If it is not understood how technology works and the necessary experts and professionals are not available, municipality is afraid of what will happen in operation. Municipality representatives admit that there have already been cases with a simple system like a pellet boiler. It is difficult to find suitable professionals who are able to keep the system operating properly.

Municipalities struggle to support large energy projects independently, making government support essential for carbon-neutral transitions. State backing not only improves economic viability but also helps gain public support for new energy initiatives.

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 approach of this study enables a better understanding of municipal energy systems and its dynamics The results revealed significant differences in the mental models developed by the energy experts, researchers, and stakeholder groups. A summary of the key parameters of mental models by main participant segments is outlined in Table 3.11. Examples of mental models of different stakeholders are illustrated in Fig. 3.24, which is intended to illustrate the differences in the complexity of the models between the various stakeholders based on their field of activity. The results of the first workshop showed that there was a large difference of developed individual mental models between energy experts and researchers. On average, energy experts included almost 10 more factors than researchers and, on average, made 14 more connections. On average, energy experts defined more factors and made more connections; however, researchers made more connections per defined factor. The number of factors included in the energy experts' models ranged from 12 to 40. The average number of factors for all models was 25. The number of connections included in the energy expert models ranged from 20 to 74, with an average of 44. The number of factors included in the researchers' models ranged from 12 to 20. The average number of factors for all models was 15. The number of connections included in the researchers' models ranged from 22 to 43, with an average of 29.

Table 3.11

Summary of Key Parameters of Mental Models by Main Participant Segments

FCM data collection	Participant segment	# models	# factors	# connections	Density	Connections per component
First workshop	Energy experts	9	24.6	43.6	0.09	1.80
	Researchers	7	15.1	29.4	0.15	1.99
Second workshop	Stakeholder groups	10	13.1	22.4	0.15	1.71

The number of factors and connections in the participant models from the second workshop were fewer than those in the models created by energy experts and researchers in the first workshop. The connections for each defined factor were slightly smaller, but the difference was not significant. Differences in decision making and perceptions of municipal energy infrastructure and policy were observed in the mental models of different stakeholder groups (Fig. 3.24).

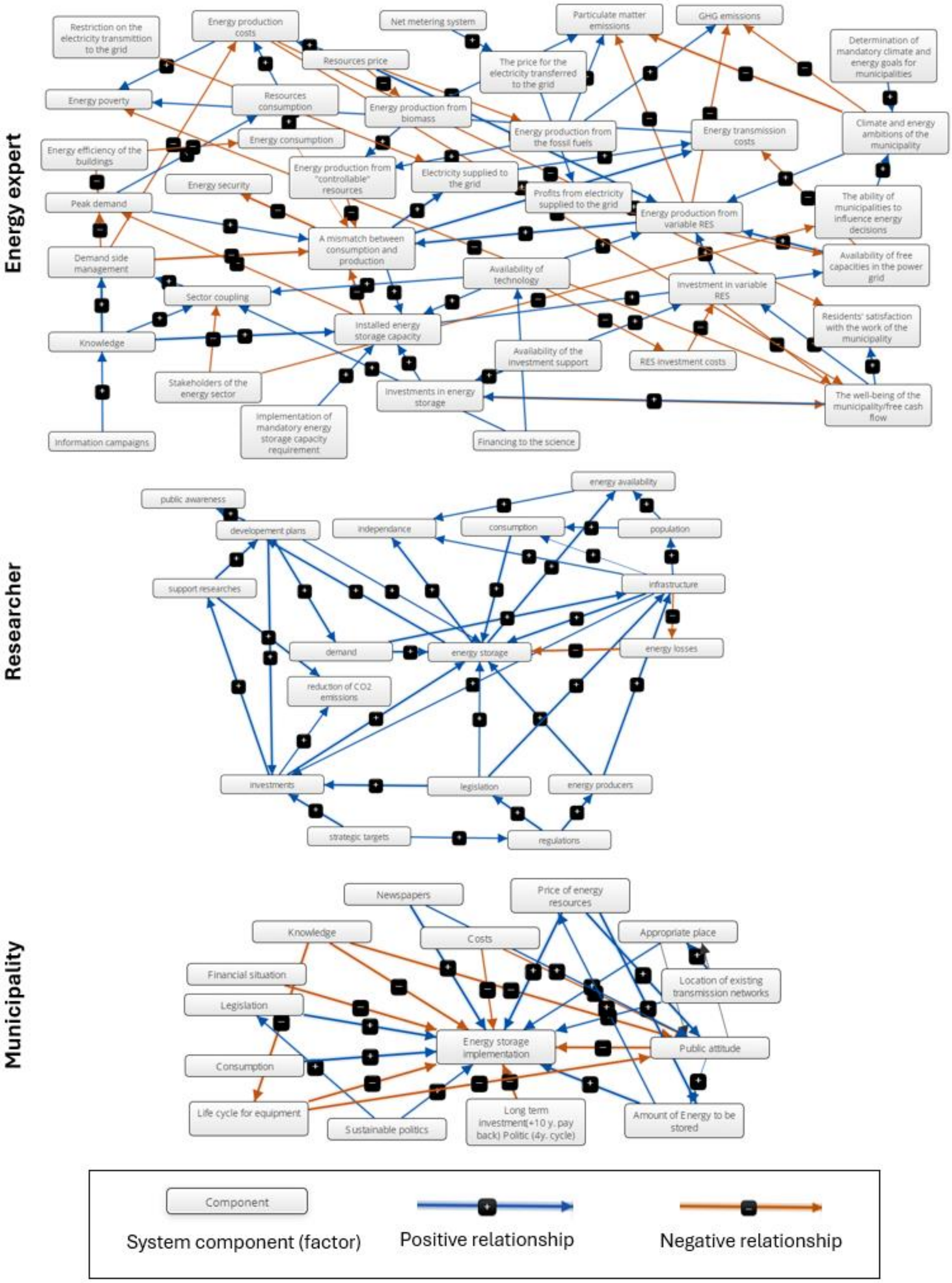


Fig. 3.24. Examples of mental models of energy expert, researcher, municipality representative, created using mentalmodeler.com online tool.

Municipalities focus more on the identification of local needs, highlighting the role of citizens' opinions and the availability of technological solutions that would specifically address local needs [149]. Whereas energy experts have highlighted the technical aspects and nationally binding climate and energy targets that drive local energy transitions [150]. However, energy experts may rely on theoretical studies and data analysis for efficient implementation of energy decarbonization strategies [150]. Researchers' mental models were primarily focused on political factors, viewing policies and governmental actions as the main drivers of local energy transitions. These mental models are more focused on external factors such as political and price considerations, rather than internal challenges.

After receiving all the individual models, they were standardized, categorized, condensed, and combined based on the methodological approach described above. In total, 458 factors were mentioned in the mental model maps, and 266 of the factors were identified as unique. The first step before combining the models was standardization and categorization to reduce information clutter. Factors similar to those mentioned in the individual models were combined and categorized. In total 21 categories were defined and are outlined in Table 3.12.

Table 3.12

Categories of Factors Mentioned in Mental Models and Their Notations

Notation	**Category**		
D1	Energy storage implementation	D11	Policies - support
D2	Knowledge, familiarity & awareness	D12	Policies - knowledge & awareness raising
D3	Energy demand	D13	Energy surplus
D4	Energy infrastructure (production, transmission, distribution)	D14	Energy dependence and security
D5	Energy price	D15	Funding availability (without support)
D6	Technology costs	D16	Occurrence of extreme circumstances
D7	Financial benefits	D17	Citizen's opinion
D8	Willingness and readiness to adapt	D18	Technology solutions
D9	Climate and energy targets	D19	Environmental impact
D10	Policies - taxes	D20	Territory availability
D11	Policies - support	D21	Other

Fig. 3.25. outlines the frequency of each category mentioned by each group of workshop participants. The majority of respondents emphasised the significance of energy storage implementation and support policies for energy storage deployment in municipalities. In contrast, tax policies, energy dependence and security, and technology solutions were only mentioned by a minority of respondents. Most energy experts and local energy transition stakeholder groups of the second workshop emphasised knowledge, familiarity, and awareness, while researchers mentioned these aspects significantly less. The same pattern is observed in the category concerning the willingness and readiness to adopt storage technologies. Most energy experts and local energy transition stakeholder groups of the second workshop consider it a crucial factor, while researchers mention it less frequently. The researchers did not discuss territory availability and energy dependence and security as factors affecting energy storage implementation. Additionally, the local energy transition stakeholder groups in the second workshop did not bring up tax policies. Energy experts are the only group that incorporates elements from all categories into their mental models. However, energy experts mentioned the category of territory availability less frequently.

The factors were categorised, and the individual models of the participants were then condensed and simplified. The condensed mental model of all workshop participants comprises 20 categories and 183 connections linking these categories.

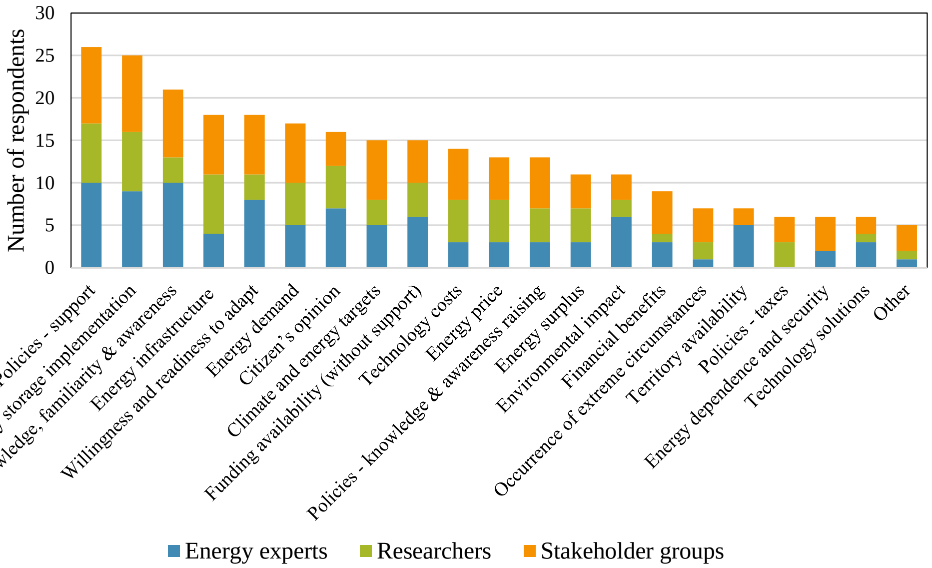


Fig. 3.25. Inclusion of the specific categories in individual models.

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. Centrality indicates the extent to which a given factor is important or central in the context of other factors and reflects the cumulative strength of connections with other factors. The higher the value of the centrality index, the greater the individual weight of the factor in the model. In general, a higher centrality index value indicates the importance of a factor to other factors with which it is related. Fig. 3.26. illustrates the centrality profile for each group – energy experts, researchers and local energy transition stakeholders. The centrality profiles for each group were different.

For energy experts, the most central categories were energy infrastructure and energy storage implementation, knowledge, familiarity & awareness, climate and energy targets, willingness and readiness to adapt. Similarly, also 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 & 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, also energy experts acknowledged knowledge, familiarity & awareness as one of the most important factors influencing energy storage deployment in local energy infrastructures. However, researchers more emphasize energy price and support policies as the key driver for change.

When analysing the combined outcomes of mental models, energy infrastructure emerged as the most pivotal factor, followed by support policies, climate and energy targets, and citizens' opinions. Signaling that all four aspects of sustainability - technical, economic, environmental, and social factors are considered equally important. Categories such as energy dependence and insecurity, territorial availability and environmental impact were mentioned less frequently and therefore appeared to be the least central factors in the mental models of all the research groups in the study.

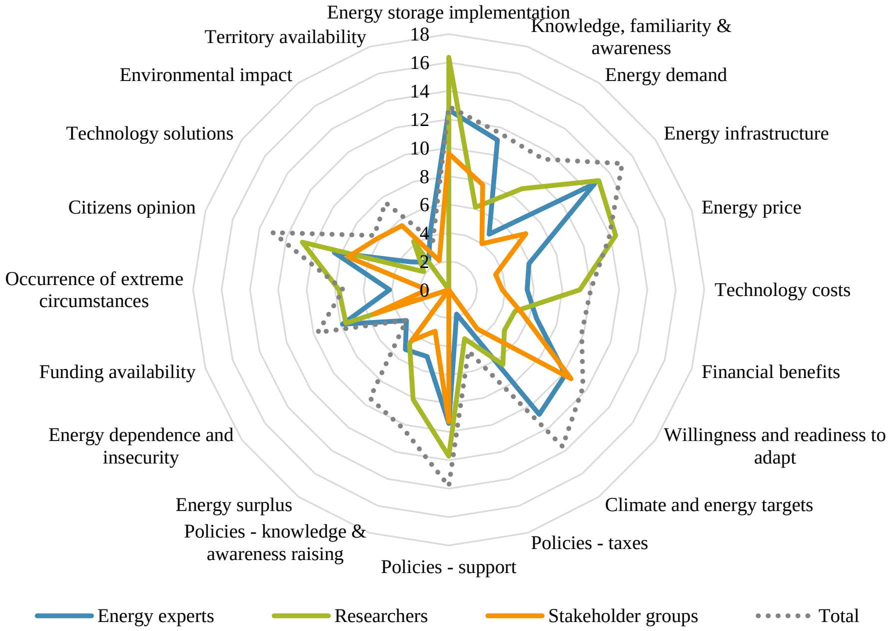


Fig. 3.26. Centrality profiles of defined categories.

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.

FCM is a valuable tool for identifying feedback loops and conceptualizing local energy system dynamics. Integrating mental models into system dynamics modeling enhances understanding of causal interconnections, delays, and influences. [151]. This approach helps to identify unintended consequences and latent interdependencies that may be overlooked in formal analysis.[152]. Examining stakeholders' mental models supports the design of tailored energy policies for better decision-making.

3.5. Climate and energy policy

The transition of the overall economy toward climate neutrality relies on both broad strategic actions and localized policies. To evaluate the progress of EU member states in achieving Green Deal objectives, a Kaya identity decomposition analysis was conducted. Afterwards, a novel climate and energy policy risk assessment model was introduced, tested through a case study analysis assessing the effectiveness and challenges of various policies in Latvia.

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. 3.27. All countries have been able to reduce the amounts of GHG emissions over the last decade when comparing GHG emission levels in 2019 with 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.

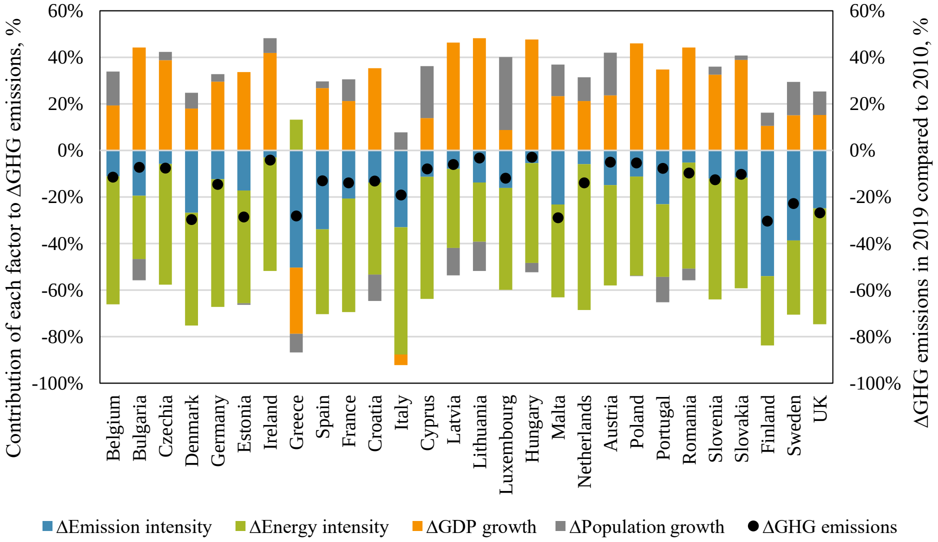


Fig. 3.27. Kaya identity decomposition for the EU-28 countries.

The Baltic States are among the lower income countries when GDP (in PPS) per capita is compared with other EU countries [153]. Therefore, more emphasis is placed on stimulating long-term economic growth in these countries in order to achieve the increase in prosperity and reach the level of more developed countries. As a result, the Baltic states may face greater pressure to maintain this dual control relationship between climate change measures and economic growth stimulation. In order to investigate how the Baltic states deal with these counter-effects, a more in-depth analysis is conducted for Latvia, Lithuania and Estonia to observe the annual changes in Kaya identity factors and to analyze the short-term effects on GHG emissions.

Summary statistics of changes in Kaya identity indicators for the Baltic states are presented in Table 3.13. From the comparison of the main Kaya identity indicators, it can be seen that Latvia has the lowest emission intensity compared to the other Baltic States. However, Latvia showed the slowest progress in reducing emission intensity over a ten-year period. The energy intensity indicator is similar for all countries and is almost at the same level in 2019. Historically, Estonia has the highest GDP per capita, followed by Lithuania and Latvia, which have similar income levels. The highest population is observed in Lithuania, while the lowest is observed in Estonia. Both Latvia and Lithuania experienced a significant decrease in the total population, while no significant changes in the number of inhabitants were observed in Estonia during the period from 2010 to 2019.

Table 3.13

Summary Statistics on Changes in Kaya Identity Indicators for the Baltic States

	2010	**2019**
GHG emissions (MtCO_2 eq)		
Latvia	12.28	11.54
Lithuania	20.89	20.22
Estonia	21.02	15.02
Emission intensity (GHG tCO_2eq per consumed energy toe)		
Latvia	2.65	2.48
Lithuania	2.95	2.59
Estonia	3.72	3.11
Energy intensity (Consumed energy toe per GDP MEUR)		
Latvia	0.23	0.17
Lithuania	0.23	0.18
Estonia	0.32	0.19
GDP growth (1000 EUR GDP per capita)		
Latvia	9.70	14.35
Lithuania	9.87	15.50
Estonia	13.23	18.71
Population (million inhabitants)		
Latvia	2.12	1.92
Lithuania	3.14	2.79
Estonia	1.33	1.32

LMDI decomposition results for selected countries are summarized in Table 3.14. In Latvia (Fig. 3.28), 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.

Table 3.14

Results of the LMDI Decomposition Analysis for the Baltic States

	Latvia	Lithuania	Estonia
ΔEmission intensity	-0.79	-2.66	-3.17
ΔEnergy intensity	-3.43	-4.88	-8.9
ΔGDP growth	4.66	9.27	6.18
ΔPopulation growth	-1.18	-2.41	-0.11
ΔGHG emissions	-0.74	-0.67	-6.00

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.

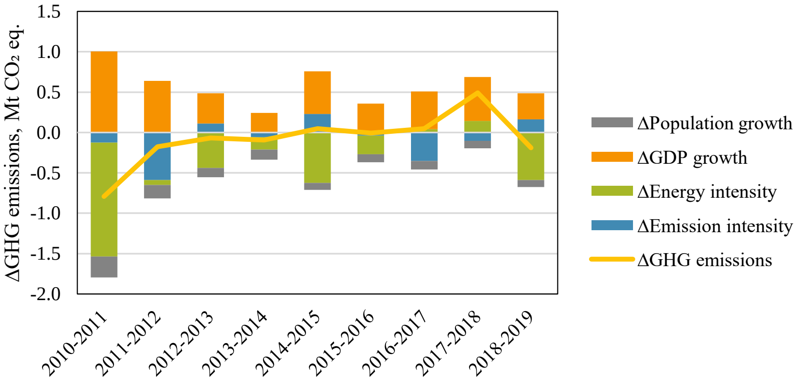


Fig. 3.28. Year-to-year Kaya identity decomposition for Latvia.

Lithuania (Fig. 3.29.) recorded the second lowest progress in the EU, where total GHG emissions fell by only 3.2% in 2019 compared to 2010. Improvements in energy efficiency (-4.91) and adaptation of renewable energy measures (-2.66) could not compensate for increasing economic activity (9.33) in this period, where a significant increase in GDP drove up GHG emissions. However, the decline in population growth (-2.43) during the period contributed to the modest cumulative GHG emission reduction results. Following the closure of the Ignalina nuclear power plant in 2009, the Lithuanian energy sector underwent significant restructuring. The decrease in primary energy production was largely replaced by fossil fuels and higher volumes of energy imports [154]. Since 2010, Lithuania has made greater efforts to increase the share of renewable energy resources by increasing the capacity of wind turbines and promoting biofuels. However, the greater impact on the reduction of GHG emissions came from energy efficiency measures, which were more pronounced especially in the period from 2011 to 2013 and from 2018 to 2019, when energy intensity in Lithuania decreased significantly.

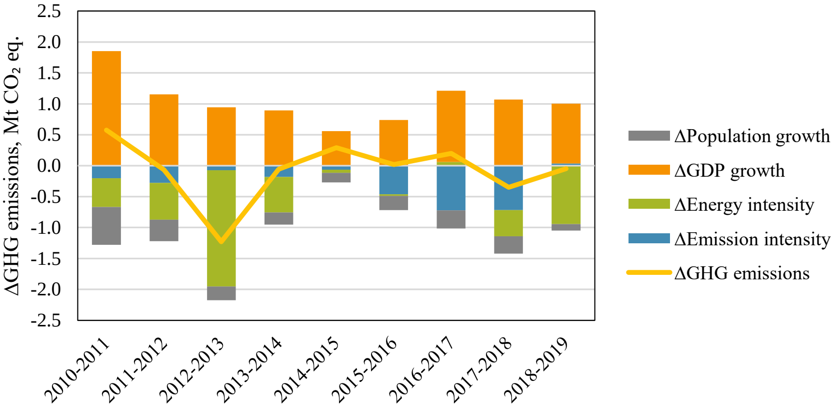


Fig. 3.29. Year-to-year Kaya identity decomposition for Lithuania.

In Estonia (Fig. 3.30.), the largest impact among Kaya identity decomposers was the decrease in energy intensity (-9.39). The overall changes in GHG emissions in Estonia on an annual basis showed much greater variability compared to the other Baltic States. The variability can be largely explained by the changes in the amounts of electricity generated from combustion fuels such as oil shale, which account for about 80% of the total primary generated energy in Estonia. In 2013 and 2017, when there was a record increase in electricity generation from combustible fuels in Estonia, total GHG emissions increased significantly in the representative years. Similarly, in 2015, when gross electricity generation from combustible fuels decreased by 20%, both emission intensity and total GHG emissions decreased significantly. Overall, Estonia showed the highest progress in reducing GHG emissions compared to the other Baltic States, achieving a reduction of 21.02 million tons of CO_2 equivalent or 29% in 2019 compared to 2010.

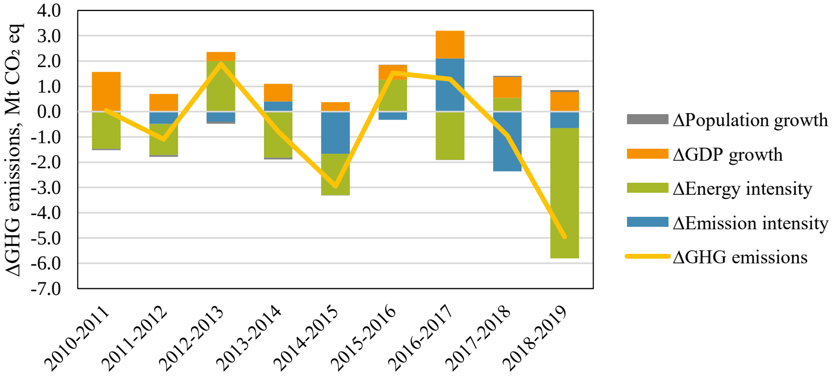


Fig. 3.30. Year-to-year Kaya identity decomposition for Estonia**.**

Although all three Baltic states have similar political and economic structure, geographical conditions and historical development background, the results of Kaya identity decomposition analysis reveal differences between Latvia, Lithuania and Estonia. The differences in the results can be explained by the significantly different energy production structures in each country. The Latvian energy generation sector has historically been more decarbonised compared to Lithuania and Estonia due to the high share of hydropower generation in the overall primary energy production balance. It is also represented in historically significantly higher share of RES. As a result, in Latvia the LMDI factor of emission intensity contributed to changes in GHG emissions to the lower extent than it is observed for Lithuania and Estonia. As Lithuania and Estonia have higher untapped potential to improve emission intensity, this factor has a higher impact on GHG reduction targets compared to Latvia. Another difference between countries can be observed in the impact of the GDP growth factor on total GHG changes. The results show that for Latvia and Lithuania, which have lower income levels compared to Estonia, economic growth was the main factor driving GHG changes over the last decade. This indicates that policies in Latvia and Lithuania were aimed at achieving higher economic gains at the expense of lower environmental protection activity.

GHG emission forecasts for the Baltic states

The results of the LMDI decomposition analysis are further used to predict future trajectories for changes in GHG emissions in the Baltic States. Three different scenarios are predicted for each country - the Existing Measures Scenario, the Additional Measures Scenario and the Business-as-Usual Scenario. The key assumptions and differences between the scenarios are summarized in Table 2.17. Table 3.15 summarizes the growth rates used for the Existing Measures baseline scenario.

Table 3.15

CAGRs Under "Existing Measures" Forecast

Country	EMI (α)	ENI (β)	GDP (γ)	POP (ε)
Latvia	-0.0069	-0.0190	0.0324	-0.0086
Lithuania	-0.0151	-0.0173	0.0413	-0.0138
Estonia	-0.0254	-0.0114	0.0285	-0.0010

The projected results of GHG emissions for Latvia, Lithuania and Estonia are shown in Fig. 3.31. - Fig. 3.33. 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 [155]. 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.

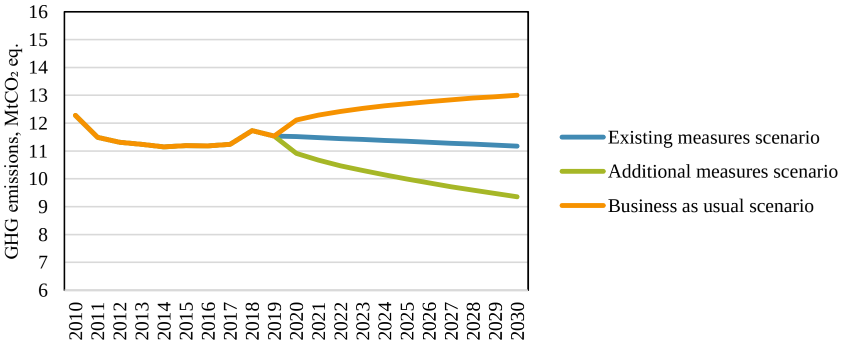


Fig. 3.31. Forecasts of GHG emissions for Latvia.

The forecast results for Lithuania (Fig. 3.32.) show a decrease in GHG emissions in all three scenarios studied. If existing policies are continued, GHG emissions in Lithuania are projected to decrease by 6.4% in 2030 compared to 2019 levels, reaching 18.9 Mt CO_2eq. Larger reductions in GHG emissions can be achieved by implementing additional measures. The projected values of the Additional Measures scenario for Lithuania show that the total GHG reduction potential for Lithuania corresponds to 10.4% reduction in GHG emissions by 2030 compared to 2019 levels.

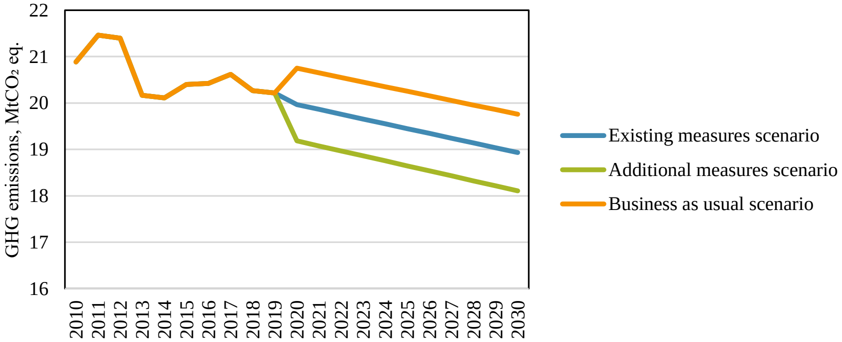


Fig. 3.32. Forecasts of GHG emissions for Lithuania.

Estonia has set a target to reduce greenhouse gas emissions by 70% by 2030 compared to 1990 emission levels. In absolute terms, Estonia plans to achieve 10.7-12.5 Mt of CO_2eq. GHG emissions by 2030, a 4.3-2.5% reduction in GHG emissions compared to 2019 levels [156]. The forecast results of this study indicate that Estonia will not meet its 2030 emission targets under the Existing Measures scenario, similar to what was observed in the case of Latvia (Fig. 3.33). The projected emission targets will only be met if additional measures are taken. Under the "Additional measures" scenario, the projected GHG emissions for Estonia will reach 10.1 Mt CO_2eq by 2030, which corresponds to Estonia's national emission target.

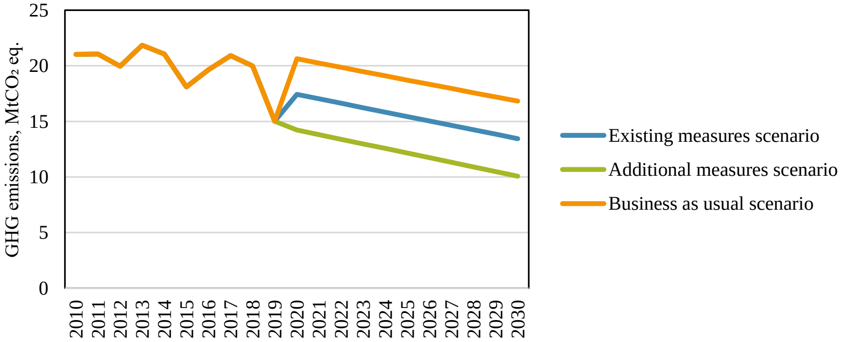


Fig. 3.33. Forecasts of GHG emissions for Estonia.

To move closer towards the achievement of EU's ambitious climate change targets, each Member State must develop a National Energy and Climate Plan (NECP). According to the rules of Regulation (EU) 2018/1999 on the governance of Energy Union and Climate Action, NECPs for the 10-year period from 2021 to 2030 were submitted by each member state to European Commission by the end of 2019 [157]. Historical progress and national targets projected in the NECPs for the Baltic States are summarized in Table 3.16. Different target trajectories can be observed between countries.

When comparing 2030 energy efficiency targets, only Latvia and Estonia anticipate a reduction in primary energy consumption from 2019 levels, while Lithuania expects an increase of over two-thirds. This rise is expected to be offset by greater decarbonization, with RES share increasing from 26% in 2019 to 45% in 2030. The decomposition analysis on changes in Kaya identity factors showed that in the past energy efficiency measures were more successful in achieving GHG emission reductions in Lithuania. Considering the projected increase in the share of RES, the emission intensity in Lithuania is expected to decrease significantly in the next decade, which will change the current decomposition of the main GHG emission impact factors. As no progress in reducing primary energy consumption has been observed in Latvia, more emphasis is placed on improving energy efficiency in the next decade. Given the much higher share of RES in Latvia compared to others, a modest decarbonization target for 2030 is foreseen for Latvia, signaling a higher importance of energy efficiency measures to promote GHG emission reductions.

Table 3.16

Historical Indicator Changes and National Targets Projected in the NECPs [158], [159], [160]

	2010	**2019**	**Target 2020**	**Target 2030**
Primary energy consumption, Mtoe				
Latvia	4.6	4.6	5.4	4.3
Lithuania	6.5	6.2	6.5	10.2
Estonia	5.6	4.7	6.5	5.5
Share of renewable energy sources, %				
Latvia	30%	41%	40%	50%
Lithuania	20%	26%	23%	45%
Estonia	25%	32%	25%	42%

Forecast of GHG emissions for the Baltic States shows that current climate policies are not sufficient to achieve the 2030 GHG emission reduction targets set in the NECPs. Therefore, additional measures should be taken to enforce GHG emission reductions in all resource consuming sectors. A preliminary NECP assessment indicates that most countries show low ambition and contribution, highlighting the need for more integrated efforts to meet EU energy efficiency targets. The lack of sector-specific targets in national climate policies hinders greater emission reductions. Specific targets and commitments should be set separately for the transport, industry, services, agriculture and household sectors 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 was validated in the five case studies of Latvian climate and energy policy.

Case 1 involved ex ante evaluation for wind energy park construction. Construction of wind energy park is a private renewable energy investment project in Latvia that projects to construct up to 35 wind turbines with a capacity of more than 100 MW by the year of 2022 and therefore, significantly increasing the overall wind energy share in the total electricity demand in Latvia [161]. Case 2 was related to ex post evaluation of Energy efficiency monitoring system program that is a policy instrument that was established in Latvia in 2017 by the Ministry of Economics of the Republic of

Latvia. The program is a part of Energy Efficiency Law which sets specific requirements for large companies and large energy consumers in order to stimulate enterprises to implement energy efficiency activities and reduce their overall energy consumption [162]. Case 3 included ex post assessment of the climate financial instrument (CCFI) that is 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. The program was introduced in order to meet the national greenhouse gas reduction targets set by the United Nations under in the Kyoto Protocol [163]. Case 4 and 5 addressed the theoretical ex ante challenge of decentralized or centralized energy system development. The question about what the most sustainable energy generation method in Latvia is and whether more emphasis should be made on promoting and supporting the distributed energy generation instead of the centralized energy systems remain unsolved. Both strategies involve issues and challenges that should be investigated in more detail to examine the risk level of each alternative.

Table 3.17. summarizes the average total risk scores for each risk indicator from the expert evaluation. These results show which risk indicator contributed the most in each risk category for each case study. The highest-rated political risk is limited long-term planning and policy objectives, often overlooking key legislative details. In the technical risk category, the top concern is the lack of employee knowledge, experience, and training. Inefficient fiscal and other policy instruments (taxation regime for the tariff determination, feed-in tariffs, quota obligation scheme, etc.) is rated as highest risk in economic risk category, risk of not achieving the reduction of carbon footprint in environmental risk category, limited public acceptance in social risk category and high bureaucracy and complex approval/administration process in administrative risk category.

Table 3.17

Average Total Risk Scores from the Expert Evaluation

		Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Political	Legal	14.00	12.75	9.00	11.20	16.40
	Regulatory	14.60	13.50	7.75	12.80	14.60
	Incentives	14.60	14.00	8.00	12.00	11.40
	Long-term	14.40	16.25	13.75	13.60	16.20
Technical	Infrastructure	7.00	7.25	8.00	10.80	5.40
	Operation	7.20	7.75	9.00	10.00	5.00
	Maintenance	9.60	7.00	9.25	11.80	8.20
	Productivity	10.60	12.25	15.00	9.00	8.00
Economic	Aid	9.00	12.00	8.25	13.00	8.20
	Policy	12.60	13.00	9.25	13.20	10.00
	Financial	8.80	11.00	10.00	10.20	9.20
	Market	9.40	10.25	12.25	13.60	10.60
Environmental	Environment	9.00	4.25	6.25	10.80	10.80
	Emissions	7.40	12.00	17.25	12.80	12.40
	Life cycle	7.40	13.25	9.50	10.00	10.00
	Resources	9.60	9.75	7.75	9.00	8.00
Social	Acceptance	17.60	11.00	8.00	10.00	7.40
	Adaptability	13.20	12.75	7.50	10.60	6.20
	Knowledge	13.00	12.25	10.50	11.00	6.20
	Labor	7.40	14.00	8.50	7.40	8.60
Administrative	Communication	13.20	10.25	7.00	9.60	9.80
	Project management	9.20	17.00	10.00	8.00	6.80
	Bureaucracy	15.40	12.25	9.75	11.80	10.00
	Institutions	10.00	17.00	7.00	8.00	10.80

The risk index results of the case study evaluation were summarized in Table 3.18. The results show that there are significant differences in the overall risk levels between the different energy policy instruments. The differences occur in all six categories of the risk index - political, technical, economic, environmental, social and administrative. Fig. 3.34. illustrates the comparison of the sub-index values determined for the different policy instruments examined.

The energy efficiency system monitoring program (Case 2) had the highest overall risk index (0.43), with particularly high scores in policy (0.55), administrative (0.49), and social (0.48) risks. The high scores obtained in these categories are consistent with the findings of the studies by Kubule et al. (2020) and Ločmelis et al. (2020), which assess the initial results of the program and identify several weaknesses related to the design of the policy instrument and program administration [162], [164]. First, the program was launched by the Ministry of Economy with considerable delay in order to meet the requirements of the EU Energy Efficiency Directive, suggesting that the government lacked the incentive and political will to promote the policy. As a result, the policy was poorly designed and lacked clear guidelines, a long-term vision, and a detailed and comprehensive description of the conditions and requirements for the program's target groups. In addition, sudden changes and additions were made to the Energy Efficiency Law website, which affected the reliability of the program and created distrust. Secondly, information about the program was poorly communicated to the main target groups, which led to confusion and limited public acceptance of the program, so that the intended objectives were not achieved. Thirdly, the overall management of the program was inadequately carried out and the monitoring system developed did not collect all the necessary data crucial for a sufficient assessment of the program objectives achieved. It can be concluded that the above factors are also reflected in the representative risk sub-indices, as the Energy Efficiency Monitoring System Program (Case 2) received the highest score in the administrative risk sub-index category and the second highest score in the social risk sub-index category compared to the other policy instruments.

Table 3.18

Summary of the Risk Index Results from the Case Study Evaluation

	Case 1	Case 2	Case 3	Case 4	Case 5
Political risk sub-index	0.56	0.55	0.34	0.46	0.58
Technical risk sub-index	0.32	0.34	0.41	0.38	0.22
Economic risk sub-index	0.37	0.39	0.37	0.47	0.33
Environmental risk sub-index	0.31	0.33	0.43	0.44	0.38
Social risk sub-index	0.49	0.48	0.36	0.38	0.27
Administrative risk sub-index	0.46	0.49	0.29	0.36	0.36
Total risk index	0.42	0.43	0.37	0.41	0.36

The lowest total risk index was found for the development of centralized energy generation (Case 5) with a risk index value of 0.36. Despite the lowest overall risk index score, this case study achieved the highest score in the political risk sub-index category with a score of 0.58. When analyzing the indicators that most influenced a high political sub-index score, it was found that almost all experts gave the highest scores to the Legal and Long-term Risk indicators. It can be concluded that the highest risk to the development of centralized energy generation is associated with the sudden changes in policies and support mechanisms by the government, as well as limited long-term planning and objectives of the centralized energy generation policies, including overlooking important details for legislation. In contrast, the development of distributed energy generation (Case 4), although the policy risk for distributed energy generation is rated significantly lower, the overall risk index reaches a value of 0.41, which is 0.05 higher than that for the development of centralized energy generation. The development of distributed energy generation (Case 4) reaches the highest economic risk sub-index. This is due to market risk, which leads to limited opportunities for economies of scale, resulting in inefficient production and operating costs (OPEX) and high capital and investment costs (CAPEX). In addition, there are currently no efficient fiscal and other policy instruments, such as an efficient tax regime for setting tariffs for distributed energy or other instruments that would promote the long-term development and profitability of distributed generation. These two factors were highlighted by the experts as the positions of particularly high risk.

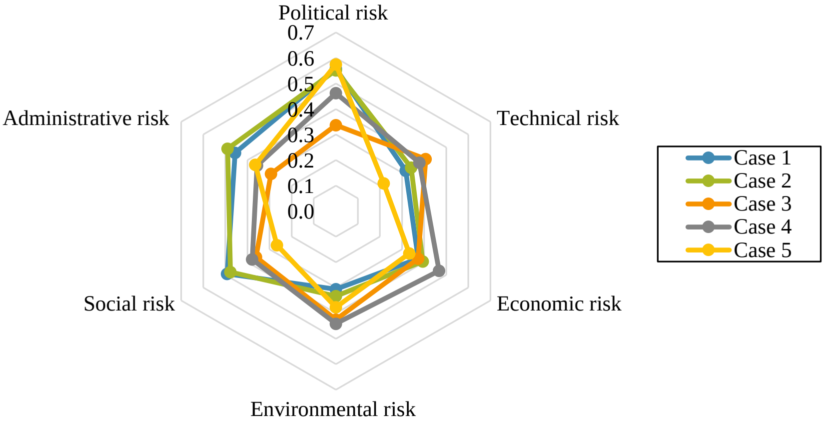


Fig. 3.34. The values of risk sub-indices from the case study evaluations.

The second highest risk index value of 0.42 was reported for the construction of a wind energy park (Case 1). In general, a similar distribution of scores was found as for the energy efficiency monitoring system program (Case 2). However, the construction of a wind energy park achieved the highest score compared to the other policy instruments, namely the score of 0.49 in the social sub-index category. The high score in this category is justified as the project has generated strong public debate and agitation over the last two years and has faced several local challenges [161]. The inadequate, insufficient and misleading dissemination of information, combined with a populist approach to communication, has led to a biased public perception and antipathy towards the project [165]. Limited public acceptance, unwillingness to change and lack of public knowledge are therefore one of the main risk factors hindering the development of the project. Apart from this, the project also faces high political risk, especially in terms of lack of clarity in the long-term vision of the regulators and lack of incentives and political will from the government to promote project implementation. In addition, the project faces a high level of bureaucracy related to existing land use regulations and permits that limit the availability of land needed to increase the capacity of installed wind turbines. [165].

The second lowest risk index value of 0.37 was found for the climate finance instrument (Case 3). However, it should be noted that the environmental risk sub-index score of 0.43 was the highest among all other risk categories for this instrument. The climate financial instrument scored the highest for the risk of not achieving emission reductions and carbon footprint reductions. This result highlights a contradiction in policy, as the main purpose of establishing the instrument was directly aimed at reducing GHG emissions in all major sectors of the Latvian economy. This leads to the conclusion that the policy instrument may have been only conceptual and failed in achieving its main objective.

CONCLUSIONS

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, confirming Thesis hypothesis. They enable a deep dive analysis of the multiple factors influencing energy policy, offering a comprehensive understanding to support informed decision-making. The results showed that the methods can be applied by national authorities to measure the effectiveness of existing climate change policies and to preliminarily assess progress towards the achievement of the climate change mitigation targets.

The overall findings on energy sustainability assessment reveal that Latvia's historical dependence on hydroelectric power plants has led to a slower progression in diversifying its renewable energy portfolio, particularly in expanding installed capacities for wind and solar energy. This reliance on hydropower has created a naive sense of comfort and sufficiency, delaying more proactive efforts to develop a broader range of renewable energy sources to enhance energy resilience and sustainability.

The cross-country comparison has shown that countries with lower levels of RES diversification such as Latvia which is highly reliable on hydro energy may be exposed to greater fluctuations in renewable energy production volumes. Moreover, some countries that have already achieved a high share of RES in their electricity generation (e.g. Latvia, Sweden, Austria) have made slower progress in the deployment of RES over the last decade. Certain countries, including Latvia, are encountering challenges in effectively embracing and putting into practice emerging RES, notably wind energy and solar PV systems. In response, these nations are prioritizing the utilization of well-established RES technologies like hydropower and biomass. However, this heightened focus on established technologies could potentially impede the future advancement of RES.

Enhancing system flexibility and focusing on energy storage solutions will play a major role in transforming renewable energy supply potential into reality. Energy storage is highlighted as the key element to accelerate the speed of decarbonization in the European Union. Thesis research results showed that currently lithium-ion batteries and thermal energy storage offer the greatest preconditions for sustainable integration into existing local energy systems. However, advanced energy storage solutions, such as hydrogen and biomethane, are emerging as progressive and strategic directions that should be incorporated into the design of future smart energy infrastructures.

As the energy transition pushes towards national energy system decentralization and highlights the importance of the local energy generation framework [30], municipalities are regarded as the primary drivers and change agents of the EU's path to climate neutrality. Thesis results showed that 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 renewable 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.

The overall results indicate that countries with initially higher GHG emissions per capita in 2010 show higher progress in reducing GHG emissions over the last decade. Rapidly growing economic activity in lower-income countries was the main offsetting factor hindering the achievement of larger reductions in GHG emissions. While significant improvements in energy and emissions intensity reductions were achieved over the 10-year period, the pace of reductions did not sufficiently offset and compensate for the impact of increasing economic activity. The results showed that over the 10-year period in the EU, the impact of energy intensity reductions had more than twice the impact on GHG emissions as emissions intensity reductions. Forecast of overall GHG emissions for the Baltic States shows that current climate policies are not sufficient to achieve the 2030 GHG emission reduction targets set in the NECPs. The preliminary assessment of the NECP targets suggests that most countries have reported low ambition and contribution, considering that more integrated efforts are needed to collectively achieve the EU energy efficiency targets. 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, public and other sectors in order to construct more effective long-term energy and climate policies.

Latvia's industrial sector is facing a challenge of producing more by consuming less energy. Despite significant improvements in energy efficiency in most manufacturing subsectors, reductions in energy intensity failed to counterbalance the effect of economic growth in manufacturing firms. The results suggest that changes in the three largest Latvian manufacturing sectors - wood processing, non-metallic minerals production and food processing, which together consume 89% of total industrial energy consumption - have a significant impact on the energy performance of the industry. Therefore, sectoral heterogeneity should be better taken into account in energy policy design. Different incentives could be applied to carbon intensive sectors such as non-metallic mineral production (ETS scheme) and lower carbon intensity sectors such as wood processing (commitment schemes, financing opportunities for factory upgrades).

The level and deployment of innovations in transport is the main cornerstone that differentiates the Eastern and Western European countries from the Nordic countries, which are leaders in the electric vehicle and alternative fuel vehicle market and infrastructure. Persistent development of renewable energy infrastructure in transport has helped the Nordic countries achieve the highest CO_2 emission reductions in the transport sector compared to other European countries which also includes Latvia. The poor performance of Eastern European countries was mainly due to the inefficient and carbon-intensive vehicle fleet, unsatisfactory public transport, lack of innovation, and slow transition to low-carbon alternatives. This Thesis identified several key policy measures for advancing transport decarbonization, based on the analysis conducted. These measures include: (1) facilitating the shift from private car usage to public transportation; (2) promoting electric mobility and expanding supporting infrastructure; (3) encouraging the adoption of alternative fuels; and (4) enhancing energy efficiency and achieving energy savings in the transport sector.

A carefully designed climate policy is the main cornerstone in order to turn the ambitious commitments into determined actions [166]. Each Member State has its own responsibility to establish necessary regulatory frameworks and policies in order to stimulate the achievement of climate binding targets [83]. The developed policy risk due diligence framework allows easy identification of the critical aspects in each policy, thus drawing attention to the positions that require immediate strategic action to reduce and eliminate risks.

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PAPER 1: COMPOSITE INDEX FOR ENERGY EFFICIENCY EVALUATION OF INDUSTRIAL SECTOR: SUB-SECTORAL COMPARISON

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Composite index for energy efficiency evaluation of industrial sector: sub-sectoral comparison

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ABSTRACT

The study investigates energy efficiency performance across 18 main industrial sub-sectors of Latvia in 2017. A composite index methodology was applied to develop energy efficiency index (EEI) that consists of 12 different explanatory indicators grouped in three main dimensions of energy efficiency – economic, technical, and environmental. The obtained results highlighted various opportunities for energy efficiency improvement in all the sectors of Latvian manufacturing industry. The results indicate that there is large potential for energy efficiency improvements in energy intensive sectors such as wood and non-metallic mineral manufacturing. The fundamental issues for each sector could be recognized and addressed to the policy makers.

1. Introduction

Over the past decade, energy efficiency has been one of the central elements in the policy agenda of the industrial sector since industry accounts for a significant share of global consumption of energy resources and production of greenhouse gas emissions (Price and Mckane, 2009; Trotta, 2020). “Energy efficiency first” is one of the fundamental principles set by the European Commission in order to encourage national policymakers to prioritize investments in energy efficient solutions and implement instruments for the adaption of sustainable energy practices (European Commission, 2020a). Organizations, especially in manufacturing industry, face a major challenge in allocating financial resources for the implementation of sustainable energy management practices to meet the ambitious climate goals and at the same time maintain strong financial and economic position (Marques et al., 2019; European Commission, 2016).

On top of that, in recent years in the European Union increasing attention is put towards unlocking the potential of ‘doing more with less’ strategy that aims at delivering greater production value with less consumed energy resources (European Commission, 2020c). Even though during the twelve-year period from 2005 to 2017 the amount of consumed energy in the industrial sector in the European Union decreased by 15%, some countries, including Latvia (7%), Belgium, Poland, and Germany (less than 5% in each), Austria (7%), Malta (9%), Hungary (25%) recorded a significant increase in the industry energy end use during the period (European Commission, 2020b). Moreover, while most of the Member States of the EU reduced their industrial sector energy intensity (consumed energy per unit of production value added), there was an increase in industry energy intensity observed in three countries - Latvia (9%), Greece (17%), and Hungary (24%) (European Commission, 2020b). It is clear that during the period Latvian industrial sector did not show any improvement towards reduction of energy consumption and stronger efforts are required in order to achieve energy efficiency objectives set by the European Commission. Therefore, more in-depth investigation of Latvian industrial sector is necessary to identify the potential of energy efficiency improvement in the industry and set clear guidelines for national policymakers.

The overall energy efficiency of the industry strongly depends on energy utilization practices of all the industrial sub-sectors combined. There are significant variations in energy efficiency levels across all the different manufacturing industry sub-sectors, therefore sectorial disparities should be considered when analyzing the industrial energy efficiency performance levels (Liao and He, 2018).

In the current scientific field, there is very limited amount of scientific publications that study the sub-sectoral differences of energy efficiency in industry. A vast majority of the existing researches on energy utilization efficiency in industrial manufacturing do not account for sectoral heterogeneity, as a result obtaining insufficient conclusions. This study aims to perform an in-depth analysis of all the relevant sub-sectors of Latvian manufacturing industry in order to investigate sector-specific disparities that would allow government to develop more efficient energy efficiency policies. The novelty of this study lies not only by

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incorporating the sub-sectorial analysis but also by choosing an innovative methodological approach, i.e., the construction of the composite index to measure energy efficiency performance levels across individual manufacturing sectors. Composite indices are widely used in numerous sustainability studies, however, to the authors' knowledge there are no similar studies done in Latvia that would use composite index methodology for sub-sectoral energy efficiency measurement. Therefore, this study presents that the same methodology is suitable and could be applied also in energy efficiency studies. More importantly, the method could serve as a useful and comprehensive tool during the development of national energy policies for a country's industrial sector.

2. Methods and data

Energy efficiency index (EEI) in this study is defined as a tool that evaluates energy efficiency performance across different manufacturing sectors in Latvia. It is a composite measure that consists of various independent indicators grouped in relevant explanatory dimensions. The construction of a composite index is a complex process that involves accurate choice of methodological approach and calculation procedures (Lemke and Bastini, 2020; Mazziotta and Pareto, 2013).

The model which is proposed in this study is based on methodological approaches used in similar studies on the development and application of composite sustainability indices. The presented methodology combines best practices from both - the academic studies (Barrera-Roldán and Saldívar-Valdés, 2002; Krajnc and Glavič, 2005; Mazziotta and Pareto, 2013; Razmjoo et al., 2019) and internationally recognized sustainability composite indices of the world's top international organizations such as United Nations (Human Development Index), European Commission (EU Eco-Innovation Index), World Economic Forum, and others (Global Competitiveness Index 4.0) (Gilijum et al., 2017; Lemke and Bastini, 2020). Since there exist various composite index construction techniques, when making a decision on the choice of the most appropriate method, the authors looked at the explanation behind the chosen methods for internationally recognized sustainability composite indices (by studying technical manuals and methodology reports), and evaluating them critically with respect to the practices utilized in the academic papers and studies. Therefore, ensuring a link between the science and politics and investigating index application in practice by public authorities and international organizations.

Fig. 1 illustrates six main chronological steps that are applied in the development of the composite energy efficiency index. The calculation procedure of the composite EEI in this study follows the below-mentioned steps. The proposed procedure of the composite index calculation resembles the methodological approach used in the sustainability evaluation studies by Barrera-Roldán and Saldívar-Valdés (2002), Krajnc and Glavič (2005), Mazziotta and Pareto (2013), Razmjoo et al. (2019).

2.1. Selection of the indicators, data collection and processing

At first appropriate indicators that are significant determiners of energy efficiency were selected. Based on data availability, in total data for 12 indicators on 18 different Latvian manufacturing sectors were collected.

Table 1
Selected Latvian manufacturing industry sectors of the study.

NACE code	Sector
B	Mining and quarrying
C10–C12	Manufacture of food products; beverages and tobacco products
C13–C15	Manufacture of textiles, wearing apparel, leather and related products
C16	Manufacture of wood and cork products; manufacture of articles of straw and plaiting materials
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C20	Manufacture of chemicals and chemical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22	Manufacture of rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment
C29	Manufacture of motor vehicles, trailers and semi-trailers
C30	Manufacture of other transport equipment
C31–C32	Manufacture of furniture; other manufacturing

Data on manufacturing sectors were classified according to NACE Rev. 2 classification that is generally accepted statistical classification of economic activities in the European Community (European Commission, 2008). Table 1 lists all the selected manufacturing sectors considered in the study.

Data on most of the selected indicators were collected from Eurostat database, except for the data on purchases of energy products and number of ISO 50001 registered companies that were gathered from Central Statistical Bureau of Latvia (CSB) and International Organization for Standardization (ISO) databases accordingly. Table 2 summarizes data sources of the selected indicators.

Almost all the data were selected for the year 2017, except for data on environment protection activity from Eurostat's CIS questionnaire. Since data on this indicator is not updated systematically on a yearly basis (Gilijum et al., 2017), the latest available data were collected.

Missing values for the year 2017 (due to data confidentiality) for the manufacture of computer, electronic and optical products sector (NACE code: C26) were substituted with the numbers from 2015 that was the latest available data on the sector. In the sensitivity analysis it was evaluated that it did not have an impact on the obtained results of the study. There were no other missing values detected in dataset of the study.

2.2. Classification of the indicators

The previous researches have explored that there are various energy efficiency influencing factors such as economic power, structure of used energy resources, energy costs, technological advancement, existing legislation, and many others (Liao and He, 2018). The indicators for this study were selected based on the identified factors that impact energy efficiency in the industry from the performed literature review in the

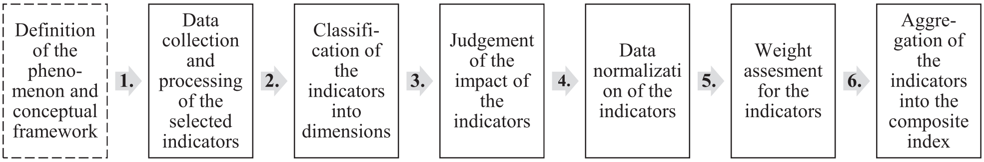


Fig. 1. Key steps for the construction of the composite index. Author's developed based on Barrera-Roldán and Saldívar-Valdés (2002), Krajnc and Glavič (2005), Mazziotta and Pareto (2013), Razmjoo et al. (2019).

Table 2
Classification of selected indicators and data sources.

Dimension	Indicator	Variable	Data source	Data code
Economic	Value added per energy use	Value added at factor cost/Net domestic energy use	Eurostat	sbs_na_ind_r2, env_ac_pefa04
	Generated turnover per energy use	Turnover/Net domestic energy use	Eurostat	sbs_na_ind_r2, env_ac_pefa04
	Energy costs	Purchases of energy products/Turnover	CSB & Eurostat	SBG010 sbs_na_ind_r2
	Energy taxes per generated turnover	Energy taxes/Turnover	Eurostat	env_ac_taxind2, sbs_na_ind_r2
Technical	Investment per energy use	Gross investment in existing buildings, structures, machinery and equipment, construction and alteration of buildings/Net domestic energy use	Eurostat	sbs_na_ind_r2, env_ac_pefa04
	Share of ISO 50001 registered companies	Number of ISO 50001 registered companies/Total number of companies	ISO/TC & Eurostat	09. ISO Survey, sbs_na_ind_r2
	Share of large size companies	Number of enterprises with 250 persons employed or more/Total number of enterprises	Eurostat	sbs_sc_ind_r2
	Energy use per employee	Net domestic energy use/Number of employees	Eurostat	env_ac_pefa04, sbs_na_ind_r2
Environmental	Greenhouse gas intensity	Greenhouse gases in tons/Value added at factor cost	Eurostat	env_ac_ainah_r2, sbs_na_ind_r2
	Use of fossil energy resources	Fossil energy products/Total energy products	Eurostat	env_ac_pefasu
	Environment protection activity	Percentage of companies that eliminated energy consumption or CO_2 emissions by innovation activities within the organization	Eurostat/CIS questionnaire	inn_cis9_env
	CO_2 productivity	Generated turnover/Tons of CO_2 emissions	Eurostat	sbs_na_ind_r2, env_ac_ainah_r2

scope of this study (Liao and He, 2018; Marques et al., 2019; Mulder and de Groot, 2013; Price and Mckane, 2009; Trotta, 2020) and based on the following criteria - data availability on the industry sub-sectors, reliability of the statistical data sources, data topicality (the latest available and most current data), as well as according to the holistic research approach to account for both direct and indirect factors that influence energy efficiency (Barrera-Roldán and Saldívar-Valdés, 2002). Using the top-down research approach, three main dimensions of sustainable energy efficiency were singled out - economic, technical and environmental dimension. As a result, all the selected indicators were grouped according to the determined dimensions. Table 2 lists the selected indicators according to their belonging to a particular dimension.

Division in dimensions is widely used in composite sustainability index application studies (Barrera-Roldán and Saldívar-Valdés, 2002; Cîrstea et al., 2018; Krajnc and Glavič, 2005), therefore the same approach was incorporated in this study. It allows to develop a broader and more comprehensive view on the key elements of energy efficiency.

Economic dimension reflects sector's ability to generate turnover and value-added per unit of consumed energy. As well as, it considers the expenses related to the amount of energy used (measured by purchases of energy products) and energy taxes relatively to production output. Viability of the economic dimension is crucial to EEI in order to evaluate if consumed energy is adequate to the generated economical contribution to the industry. Sectors with high economic power are less dependent on the amount and expenses of the consumed energy in their production process. Stronger economic and financial stability of a sector might encourage to implement more sustainable practices in the energy management in manufacturing.

Technical dimension incorporates several essential aspects that are related to the total factor performance of production process. It includes both technical and human capital inputs. Both of these factors are significant determinants of the design and capacity of the sector's manufacturing process. Technical efficiency of production processes is measured by the amount of investments made in facilities and machinery per unit of consumed energy. Thus, the indicator measures sector's investment rate in more efficient manufacturing machineries and production facilities. The share of companies that have introduced and implemented ISO 50001 standard characterizes if companies in corresponding sectors are encouraged to implement more efficient energy management practices. Moreover, share of large size companies is also included in technical dimension in order to consider organizational and structural factors of a sector. Additionally, indicator that measures energy use per employee is included to evaluate energy consumption relatively to labor inputs.

Table 3
Impact evaluation of the indicators on EEI.

Dimension	Indicator	Impact on EEI
Economic	Value added per energy use	+
	Generated turnover per energy use	+
	Energy costs	–
	Energy taxes per generated turnover	–
Technical	Investment per energy use	+
	Share of ISO 50001 registered companies	+
	Share of large size companies	+
	Energy use per employee	–
Environmental	Greenhouse gas intensity	–
	Use of fossil energy resources	–
	Environment protection activity	+
	CO_2 productivity	+

Environmental dimension reflects the impact of a sector on the ecosystem and atmosphere. It is measured by the greenhouse gas emission intensity, share of fossil energy resources, and CO_2 productivity. As well as, it considers sector activity in the implementation of environment protection activities with an aim to reduce energy consumption or carbon footprint. Sectors that produce lower impact on the environment are more sustainable and therefore closer to achieving higher energy efficiency.

2.3. *Judgement of the impact*

When indicators are identified and grouped into the dimensions, it is necessary to evaluate the potential impact and relationship of the indicators on the EEI (Krajnc and Glavič, 2005). All the selected indicators were divided in two groups – those of having a positive influence and those of having a negative influence on a sector's goal of reaching higher energy efficiency.

In order to understand whether an indicator is positively or negatively correlated with EEI, the effect on EEI of each indicator is assessed by the following rule of thumb. An indicator has a positive influence on EEI if its increasing value accelerates the increase of energy efficiency. On the other hand, an indicator has a negative influence on EEI if its increasing value hinders the improvement of energy efficiency (Krajnc and Glavič, 2005). Table 3 summarizes the results from the impact evaluation. The categorization according to the indicator's impact on EEI is required since it determines the calculation methodology for data normalization in the further steps of EEI construction.

2.4. Data normalization

Data normalization is necessary in order to eliminate ambiguity of the indicators and achieve more consistent results. Data normalization transforms all the different scales of the indicators into a one common scale and therefore makes all the different indicators comparable among each other (Krajnc and Glavič, 2005). As a result, after data normalization procedure all indicators are compatible to a common composite index.

There are several normalization techniques available such as standardization (z-scores), ranking, rescaling (min-max transformation), distance-based normalization. In this study data normalization is performed using min-max transformation based on the following reasons. Mazziotta and Pareto (2013) in their study on methods for constructing composite indices develop an algorithm for choosing the most appropriate data transformation techniques when constructing a composite index. The authors claim that rank, min-max or z-score normalization is recommended for the relative comparison studies (Mazziotta and Pareto, 2013) which is the exact case of this study since it focuses on the relative comparison analysis of different sub-sectors of one industry. Compared to other normalization techniques, normalized values according to the min-max normalization fall into one common interval, since min-max normalization ranks the values in the range of 0–1, therefore it allows for easy interpretation of obtained results (Harik et al., 2015) which could be directly used by the policymakers that are the direct target group of this study. Moreover, Pollesch & Dale (2016) in their study on the analysis of different normalization techniques in sustainability assessment concludes that both z-score and min-max normalization are less complicated to implement on the collected research data set because these techniques do not require predefined benchmarks and targets or conversion factors that are necessary in other normalization methods (Pollesch and Dale, 2016).

Min-max normalization technique is also commonly used in the methodologies of well-known international indices such as eco-innovation index (proposed by European Commission), human development index (proposed by United Nations Development program), and others. Since one of the main goals of this study is to construct an index that could be utilized and applied during the policy designing and implementation process by the government or other public authorities, then given the above mentioned advantages of min-max normalization and its common application in sustainability assessment, it was found to be the most appropriate method for EEI.

Each indicator is normalized according to the following equations. Indicators of positive influence are normalized using Eq. (1).

$$I_N^+ = \frac{I_{act} - I_{min}}{I_{max} - I_{min}} \tag{1}$$

Indicators of negative influence are normalized using Eq. (2).

$$I_N^- = 1 - \frac{I_{act} - I_{min}}{I_{max} - I_{min}}, \tag{2}$$

where I_N^+ is a normalized indicator of a positive influence on EEI, I_N^- is a normalized indicator of a negative influence on EEI, I_{act} is the actual value of an indicator in a particular sector, I_{max} is the maximum value of an indicator from all the sectors, I_{min} is the minimum value of an indicator from all the sectors.

2.5. Weight assessment

After all the indicators are normalized accordingly, weights are assigned to each indicator. There are several methods available when choosing the most appropriate weighting methodology, however, there is no single most convenient weighting method since weighting is considered to be highly controversial (Singh et al., 2007).

In environmental and sustainability studies equal weights are often used to address the equal importance of all the factors included. However, equal weighting might not be sufficient in more complicated composite indices since it might fail to account for correlations among various sub-indicators (Singh et al., 2007). Other common methods like expert weighting and analytic hierarchy process (AHP) method are based on subjective weight evaluation and therefore could generate highly sensitive and biased results that might lead to incorrect data interpretation and conclusions (Mazziotta and Pareto, 2013).

In this study equal weighting was applied. Equal weighting is based on Sustainable Development concept that emphasizes the equal importance of all the factors involved (Barrera-Roldán and Saldívar-Valdés, 2002). All the selected indicators and dimensions were assumed to have an equal contribution to the development of EEI since all of them are interconnected and create synergies that jointly impact energy efficiency.

2.6. Aggregation of the indicators

The final calculation step is the aggregation of the obtained normalized and weighted indicators. At first indicators are aggregated in the corresponding dimensions using the Eq. (3).

$$I_D = \sum w \times I_N^+ + \sum w \times I_N^-, \quad \mathrm{w} = \frac{1}{n_I} \tag{3}$$

where I_D is the sub-index of a particular dimension, w is the value of determined weight of an indicator, I_N^+ and I_N^- are normalized indicators in each dimension, n_I is the number of indicators in a dimension.

Then the final composite energy efficiency index (EEI) is determined by the accumulated sum for each of the dimension with its corresponding weight. The calculation is done according to Eq. (4).

$$EEI = \sum w \times I_D, \quad \mathrm{w} = \frac{1}{n_D} \tag{4}$$

where EEI is final composite energy efficiency index, w is the value of determined weight of a dimension, n_D is the number of dimensions.

Basic hierarchy of EEI is illustrated in Fig. 2. It portrays the structure of the EEI with its representative sub-dimensions and their explanatory indicators.

3. Results and discussion

Energy efficiency index (EEI) was constructed to evaluate and depict energy efficiency performance across the 18 main manufacturing sectors in Latvia. EEI has been determined for the year 2017 based on the latest publicly available data.

In total twelve indicators were considered and grouped into 3 separate sub-dimensions - economic, technical, and environmental. Each sub-dimension consisted of 4 explanatory indicators and then the three sub-dimensions were aggregated into the Energy Efficiency Index (EEI). Division into dimensions allowed to capture the different aspects of energy efficiency and compare their impact on the overall energy efficiency performance for each sector.

The applied methodology allows for simple and comprehensive interpretation of the obtained results. According to Krajnc and Glavič (2005) the results of the composite index should be interpreted in the following way – the higher the value of the index, the greater the sector's improvement towards energy efficiency (Krajnc and Glavič, 2005). The same applies for the values of dimension sub-indices. Therefore, the higher a sector scores on each dimension separately, the greater value it reaches for the overall EEI. Higher EEI value indicates sector's better performance of energy efficiency relative to other sectors of the same

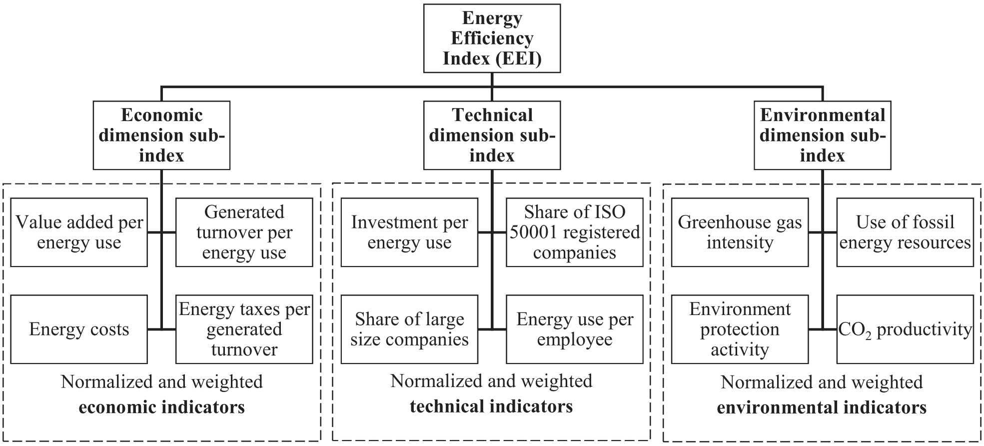


Fig. 2. Basic EEI construction hierarchy. Author's developed based on Krajnc and Glavič (2005).

Table 4
The obtained results for economic, technical and environmental dimensions and EEI.

Sector	Economic dimension sub-index	Technical dimension sub-index	Environmental dimension sub-index	Energy efficiency index (EEI)
Computer, electronics, optics	1.00	0.38	0.72	0.70
Electrical equipment	0.49	0.50	0.58	0.52
Pharmaceuticals	0.44	0.75	0.37	0.52
Printing and media	0.41	0.54	0.56	0.50
Machinery and equipment	0.39	0.42	0.64	0.48
Motor vehicles and trailers	0.46	0.44	0.53	0.48
Fabricated metals	0.40	0.39	0.51	0.43
Rubber and plastics	0.34	0.40	0.53	0.42
Other transport equipment	0.18	0.37	0.58	0.38
Textiles, clothing, leather	0.38	0.30	0.40	0.36
Food, beverages and tobacco	0.32	0.31	0.44	0.36
Paper	0.36	0.30	0.39	0.35
Furniture and other manufacturing	0.28	0.32	0.42	0.34
Chemicals	0.27	0.19	0.54	0.33
Basic metals	0.25	0.21	0.48	0.32
Mining and quarrying	0.13	0.30	0.28	0.24
Wood and cork	0.03	0.08	0.56	0.23
Non-metallic minerals	0.03	0.03	0.06	0.04
Average	**0.34**	**0.35**	**0.48**	**0.39**

Units of measurement of each dimension: 1.0 being the highest and 0.0 the lowest grade.

industry.

Table 4 lists sub-indices of each dimension for all the sectors of the Latvian manufacturing industry. Fig. 3 illustrates the results. Overall, all sectors indicate weak energy efficiency with the industry average EEI score of 0.39. Environmental dimension sub-index with an average score of 0.48 has the most significant contribution on the overall EEI value. 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.

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), machinery and equipment manufacturing (0.48) sectors. Five leading sectors reached dominating values in each of the dimension sub-indices which consequently lead to the higher aggregated 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. Meaning that while a sector might achieve the highest value in one dimension, it lacks certain factors to dominate at the same level in other 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), chemicals and chemical products manufacturing (0.33) sectors. Average EEI values ranging from 0.34 to 0.48 were obtained for the rest of the sectors included in the scope of this study. These values indicate that sectors with poor EEI levels are strongly influenced by the performance of leading sectors that reached the highest EEI values. It could be explained by the Pareto efficiency theory that suggest that if one sector is better off in one of the energy efficiency criteria, it consequently makes the other competing sector worse off.

Computer, electronics and optics manufacturing sector stood out as being the only sector that reached the highest possible value (i.e., 1) in the economic dimension. In no other dimension the maximum value of 1 was reached by any of the sectors. Computer, electronics and optics manufacturing sector was the absolute leader in the economic dimension. Electrical equipment manufacturing sector and motor vehicles and trailers manufacturing sector reported second and third highest numbers with the values of 0.49 and 0.39 respectively, which is more than twice less than for the leading position. On contrary, the sectors with the lowest economic dimension numbers were non-metallic minerals manufacturing (0.03), wood and cork manufacturing (0.03), and mining and quarrying (0.13).

In technical dimension the highest score of 0.75 was reached by pharmaceuticals manufacturing sector partly because the sector is concentrated with more large size companies and companies that have implemented ISO 50001 standard. Comparatively high values in technical dimension was recorded also for printing and reproduction of recorded media sector (0.54) and manufacture of electrical equipment sector (0.50) since both sectors represented high numbers in energy use per number of employee and investment made per energy use. On the other hand, the weakest numbers for technical dimension was recorded for sectors like non-metallic minerals manufacturing (0.03), wood and cork manufacturing (0.08), and chemical products manufacturing (0.19).

The leader in the environmental dimension was again computer, electronics and optics manufacturing sector (0.72) followed by machinery and equipment (0.64), other transport equipment (0.58), wood and cork products manufacturing (0.56) sectors. All these sectors performed well in indicator values of greenhouse gas intensity and share of fossil energy resources. In addition, computer, electronics and optics manufacturing sector represented record high CO_2 productivity compared to other sectors. The least environment friendly sectors were non-metallic minerals manufacturing (0.06), mining and quarrying sectors (0.28), and pharmaceuticals manufacturing (0.37).

When looking closely at sector's individual performance, the following insights could be observed. Manufacture of computer, electronic and optical products achieved the highest EEI score, mainly because of the high values it reached in economic and environment subdimension. 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 reliable on human capital and intellectual property thus, the economic value that the sector generates surpass the energy inputs that are required in the product manufacturing process. The second highest EEI score was obtained in electrical equipment manufacturing sector, followed by basic pharmaceutical products and preparations manufacturing, printing and reproduction of recorded media, machinery and equipment, motor vehicles and trailers manufacturing sectors. These sectors scored similarly on all the sub-dimensions except for basic pharmaceutical products and preparations sector that presented significantly higher results in technical sub-dimension. The results indicate that manufacturing more complex and knowledge-intensive or lightweight products result in higher energy efficiency (Zuberi et al., 2020).

On the other hand, 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 as highly energy intensive and sensitive. The generated economic value of the products produced in these sectors is insufficient to compensate the energy that was consumed in the production process of the products. As a result, 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 that is measured by the generated value added and turnover per unit of consumed energy. Therefore, the higher 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 it consumes 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 primary in energy intensive sectors.

In general, the level of total energy utilization efficiency of an industry can be investigated and explained by exploring (1) individual sector's concentration in the industry; (2) individual sector's generated monetary turnover to account for sector's energy productivity; (3) individual sector's energy intensity that is an inverse of energy productivity (Mulder and de Groot, 2013; European Commission, 1970). Fig. 4 represents the overall outlook of the Latvian manufacturing industry structure and energy intensity.

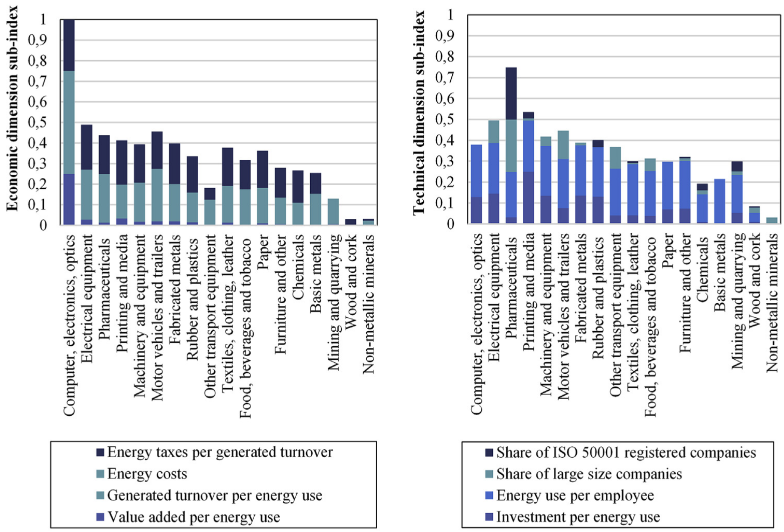
When analyzing total energy efficiency performance in manufacturing industry including all the sectors involved in the study, from the above-mentioned result analysis it can be concluded that overall the energy efficiency performance of Latvian manufacturing industry in 2017 can be considered as weak. It can mainly be explained by the country's unequally diversified structure of manufacturing industry sectors. More specifically, Latvian manufacturing industry is largely composed by energy-intensive sectors such as manufacture of wood and of products of wood and cork and manufacture of other non-metallic mineral products that constitute 58% and 16% of total net domestic energy use and 27% and 7% of total turnover of Latvian manufacturing industry respectively (see Fig. 4). However, both sectors demonstrate worst EEI in the scope of this study. Moreover, both sectors recorded the lowest values in all the dimensions and their representative indicators, except for manufacturing of wood products that reported high numbers in the environmental dimension since the sector mostly relies on the use of renewable energy resources. However, relatively high performance in the environmental dimension did not compensate the weak results in the economic and technological dimension which in result lead to low EEI in total for wood manufacturing sector. All in all, combining the EEI results from Fig. 3 and the insights on the manufacturing industry outlook and structure in Fig. 4, it can be seen that there is huge potential in improving energy efficiency in wood, wood products and cork manufacture and manufacture of other non-metallic mineral products since both sectors combined take up almost two thirds of the total manufacturing energy consumption in Latvia.

These insights suggest that in order to enhance industry's overall energy efficiency performance, extra attention should be put on these two sectors since both sectors have the highest concentration and impact in the overall portfolio of manufacturing industry sectors in Latvia. Therefore, it is recommended for the government to focus on developing sector-specific energy efficiency policies that would encourage enterprises in these sectors to implement better energy efficiency practices.

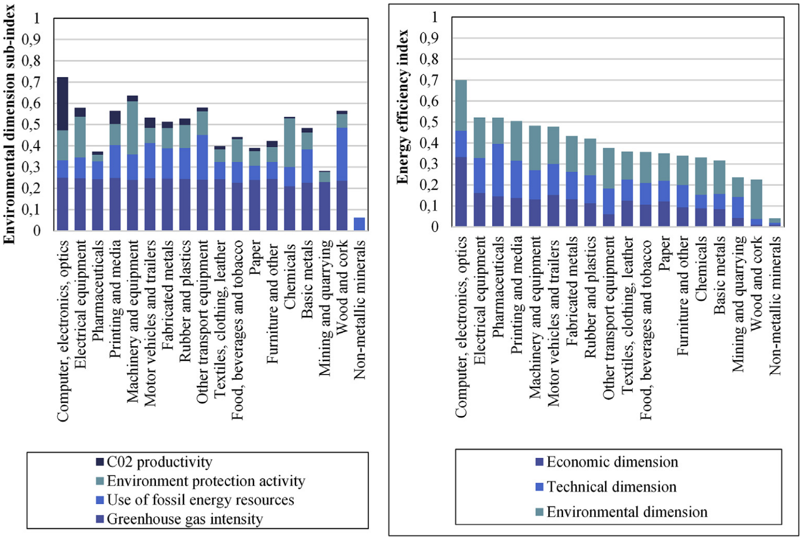
4. Conclusions

In this study 18 manufacturing industry sectors in Latvia were evaluated and compared with respect to their energy efficiency performance in 2017. The tree essential dimensions of sustainable energy efficiency – economic, technical, and environmental with four explanatory indicators in each dimension were incorporated and considered for each sector. The research simultaneously explores and analyzes indicator effects on each of the EEI dimensions, i.e., the impact of production value added, generated turnover, energy costs, and energy taxes on EEI economic dimension; the impact of investment rate, share of registered ISO 50001 standards and large size enterprises, and energy consumption per employee on EEI technical dimension; the impact of greenhouse gas intensity, share of fossil energy resource use, environment protection activity, and CO2 productivity on EEI environmental dimension.

The study showed that there exist serious disparities in the energy utilization efficiency levels across the manufacturing industry sectors in Latvia and the differences appear in all three dimensions of energy efficiency. High energy efficiency was achieved mostly in high-tech sectors that produce more sophisticated and complex products, e.g. computers, electronics, optics, and electrical equipment. On top of that, lightweight sectors that include highly automated production processes and produce serial products of relatively light weight and high economic value, e.g. pharmaceuticals, printed and reproduced media materials, likewise held considerably higher energy efficiency performance levels. On contrary, low energy efficiency was observed in highly energy intensive sectors that produce primary products with low added value, e.g. wood, non-metallic minerals (sand, gravel, clay, limestone, etc.). The developed method allows to identify unique characteristics of each sector and it provides valuable information for designing and developing efficient sector-specific energy policies and future development strategies. The obtained results highlight significant sector differences, therefore in order to accelerate the energy efficiency improvement in the



(1) Economic dimension sub-index **(2) Technical dimension sub-index**



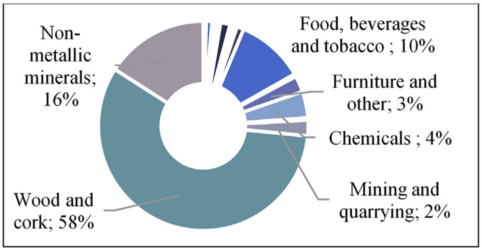
(3) Environmental dimension sub-index **(4) Energy efficiency index**

Fig. 3. Economic, technical, environmental dimension sub-indices and the overall energy efficiency index for the 18 selected Latvian manufacturing industry sectors in the year of 2017.

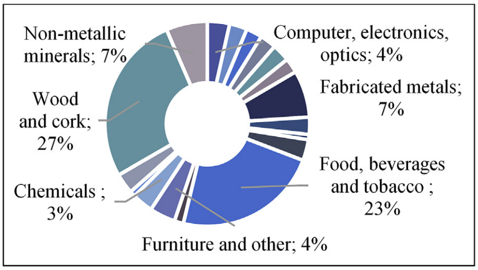
underperforming sectors, development of different policies is recommended when implementing energy efficiency legislation.

Based on the obtained results on the sector disparities in EEI sub-dimensions and their corresponding explanatory indicators, the following policy implications are discussed and recommended to the policymakers. Government should put more focus on monitoring high energy intensity sectors such as non-metallic mineral and wood product manufacturing since these sectors not only account for the highest share of total industry net domestic energy consumption but also demonstrate the lowest energy utilization efficiency. It is suggested for the government to develop and adapt policies for enhancing energy efficiency in highly energy intensive industries and reduce low energy efficiency manufacturing. By determining the factors that are significant specially for energy intensive sectors and by understanding the underlying barriers for incorporating better energy efficiency management practices in these sectors would help to implement more efficient strategies in improving country's overall manufacturing industry's energy efficiency.

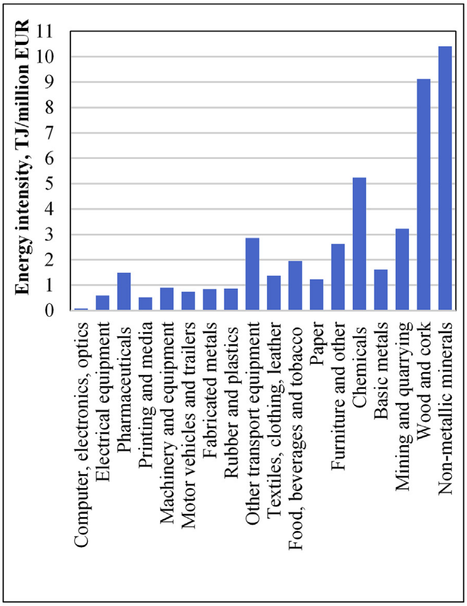
The advantage of the composite index methodology is that the developed model could be easily adjusted and modified with respect to the area and purpose of the research, as well as the interests of the main stakeholders. The model allows for the inclusion of unlimited number of the indicators, therefore the index could be supplemented with



(1) Sector's energy use as % of total industry's energy use



(2) Sector's turnover as % of total industry's turnover



(3) Sector's energy intensity, TJ/million EUR

Fig. 4. Structure of the overall Latvian manufacturing industry and energy intensities of all sub-sectors in 2017.

additional variables that would increase the explanatory power of the topic being studied. Even though the demonstrated case study tried to incorporate all the relevant aspects of industrial energy efficiency one of the main limitations that was encountered throughout the research was data availability that limited the opportunities for inclusion of various relevant indicators such as – expenditure on energy efficiency measures, availability of the latest technologies, employee training rates, implementation of energy audits, available external funding opportunities for energy efficiency activities for each sector, and others.

In further studies, the proposed method could be applied for different time periods to analyze the dynamics of each sector's progress to moving towards higher energy efficiency. In addition, the study was based on the official publicly available statistical databases, therefore similar case studies using the same data sources can be conducted in other countries. Further research could expand the scope of the study and construct indices for foreign countries as well as for the EU and/or OECD average values that would allow to compare the energy efficiency performance and developments of Latvian industry in the international perspective. Moreover, various improvements could be considered when developing methodological approach of the composite index in the further studies, e.g. utilization of different normalization or weighting method, in order to investigate the sensitivity of the obtained results when different approaches are chosen. Further research could experiment with different indicator and dimension weighting techniques where the weights would be determined through focus group discussions with experts and stakeholders of the research topic. As a result of discussions, AHP weighting method could be applied expert would rank the importance of each indicator with respect to the energy efficiency.

CRediT authorship contribution statement

Kristiāna Dolge: Formal analysis, Conceptualization, Methodology, Writing - original draft, Investigation, Data curation, Visualization. **Anna Kubule:** Conceptualization, Data curation, Investigation, Validation, Writing - review & editing. **Dagnija Blumberga:** Conceptualization, Validation, Supervision.

Declaration of competing interest

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

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PAPER 2: KEY FACTORS INFLUENCING THE ACHIEVEMENT OF CLIMATE NEUTRALITY TARGETS IN THE MANUFACTURING INDUSTRY: LMDI DECOMPOSITION ANALYSIS

energies

Article

Key Factors Influencing the Achievement of Climate Neutrality Targets in the Manufacturing Industry: LMDI Decomposition Analysis

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Abstract: The manufacturing industry is often caught in the sustainability dilemma between economic growth targets and climate action plans. In this study, a Log-Mean Divisia Index (LMDI) decomposition analysis is applied to investigate how the amount of industrial energy-related CO_2 emissions in Latvia has changed in the period from 1995 to 2019. The change in aggregate energy-related CO_2 emissions in manufacturing industries is measured by five different factors: the industrial activity effect, structural change effect, energy intensity effect, fuel mix effect, and emission intensity effect. The decomposition analysis results showed that while there has been significant improvement in energy efficiency and decarbonization measures in industry, in recent years, the impact of the improvements has been largely offset by increased industrial activity in energy-intensive sectors such as wood processing and non-metallic mineral production. The results show that energy efficiency measures in industry contribute most to reducing carbon emissions. In the future, additional policies are needed to accelerate the deployment of clean energy and energy efficiency technologies.

Keywords: decomposition analysis; LMDI; CO_2 emissions; manufacturing industry; energy policy; sustainability

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1. Introduction

The 2021 Emissions Gap Report from UN states that current targets in national climate action plans are insufficient to meet the commitments of the Paris Agreement. In fact, it is estimated that at the current rate of improvement, global temperatures will rise by 2.7 °C by the end of the century, well above the 2 °C target, and would, therefore, cause irreversible damage to the Earth's climate. To limit the rate of global warming and keep the temperature increase below 1.5 °C, global yearly GHG emissions must be reduced by at least 50% by 2030 [1].

Industry, and in particular carbon- and energy-intensive manufacturing, will play a crucial role in meeting global climate change mitigation targets. Since energy-intensive industries and power plants account for nearly half of world's total greenhouse gas emissions, they are key cornerstones in achieving net-zero carbon emission goals [2]. The constant battle between economic growth targets and climate commitments in industry makes it particularly difficult to achieve long-term sustainability in industrial companies [3,4].

The latest study assessing progress in reducing carbon emissions by European industry shows alarming results. A study by [2] analyzed CO_2 emissions data from the European Union Emissions Trading System (EU ETS) for the 13 years of operation of the program for the United Kingdom, Spain, France, Italy, and Germany, which are the largest European economies. The results show that the largest European manufacturing sectors have not yet achieved significant reductions in carbon emissions. Only a few plants have managed to achieve gradual decarbonization and reduce emissions, while a large number of companies have increased their annual emission levels. The study's findings make it urgent for

European manufacturing companies to adopt alternative technologies to restructure the energy mix currently used towards cleaner production. The authors argue that additional policies are needed to meet the binding targets of achieving net zero emissions by 2050. In addition, more in-depth research is needed to examine the key drivers of carbon emissions growth and barriers to the implementation of decarbonization measures by manufacturing firms [2].

Research on energy efficiency and decarbonization in the industrial sector is very complex due to the different production processes in the various industrial subsectors and the importance of the energy sources used for energy supply and as production feedstock. Due to this heterogeneity and the multitude of factors to be taken into account, it is difficult to make a sufficient assessment of the key factors affecting changes in the sector's energy consumption and carbon emissions [5]. Due to the fragmented nature of industry, most studies on energy efficiency and decarbonization in industry tend to narrowly focus only on a sub-sector of industry, and therefore, ignore the whole industrial energy system, which does not allow for a comprehensive assessment of the industrial pathway towards adaptation to low-carbon energy systems [6]. For industry to meet ambitious net-zero emissions targets over the next three decades, deep decarbonization is required at all levels of industrial processes and economic activity. Therefore, an integrated examination of industrial carbon emissions across all sub-sectors is crucial to shape more effective future climate policy [2].

This study aims to fill the research gap in the assessment of mitigation progress in carbon emissions from the manufacturing sector in the European Union. This study takes the Latvian manufacturing industry as a case study for assessing changes in industrial emissions using Log-Mean Divisia Index (LMDI) methodology. LMDI is applied to study the changes in energy-related carbon emissions of ten different manufacturing sub-sectors and their cumulative impact on the overall decarbonization level of Latvian industry. It allows for a comprehensive and complete assessment of industrial carbon emissions and draws relevant conclusions for a sector as a whole, leading to relevant results that can be used by governments for more efficient climate and energy policymaking. Latvian industrial energy efficiency and climate policy has undergone significant changes over the last decade [7]. Fiscal instruments, subsidies, and mandatory energy efficiency audits and monitoring have been imposed on industrial companies to promote and support decarbonization, energy efficiency, and the transition to more sustainable energy systems in manufacturing companies in order to move closer to climate neutrality goals [8]. Therefore, it is necessary to assess what progress Latvian industry has made in achieving the carbon reduction targets and whether any improvement can be observed as a result of the implemented policies. In Latvia, there is no research that uses LMDI decomposition analysis to decompose changes in energy-related CO_2 emissions from industry. Therefore, this research will make an important contribution to the general knowledge generation in the field of energy policy.

2. Literature Review

2.1. Methods for Analyzing Changes in CO_2 Emissions in the Manufacturing Industry

A lot of research has been done to analyze the factors affecting energy consumption and carbon emissions in different sectors of the economy. However, there is no consensus among scholars on a universal method for in-depth assessment of carbon emission changes in manufacturing industries.

A study by [9] developed an econometric model and analyzes different pathways of industrial carbon emissions in China through regression analysis and Monte Carlo simulation [9]. Econometric methodology is also used by [10], who built a random effects panel model to study the relationship between climate policy goals and manufacturing industry investment in energy efficiency [10]. A novel econometric method was introduced by [11], who used second-generation tests to investigate how innovation, export diversification, and fiscal decentralization affect the achievement of climate neutrality goals [11]. An advanced dual-channel supply chain network (DCSCN) equilibrium method was constructed by [12], which analyzed the effectiveness of a progressive carbon tax policy in the manufacturing industry [12].

When analyzing changes in energy intensity and carbon emissions in various sectors of the economy [13], including manufacturing industry, decomposition analysis is one of the most commonly used methods, both by scientists and international regulatory organizations, such as the International Energy Agency (IEA), European Commission, United Nations, and others [14].

2.2. Theoretical Foundation of Index Decomposition Analysis (IDA) Methods

The use of the index decomposition analysis method (IDA) has increased in energy policy and sustainability research since the 1980s, when its theoretical framework began to appear in energy studies around the world [15,16]. The method allows to measure the impact of the main factors influencing changes either in total energy consumption [17] or in the emissions [18] produced by specific sectors [16]. The method has gained its recognition in energy policy research due to several advantageous features, such as the availability of data to build the model, the ease of interpretation, and comparison of the results [19].

The methods of IDA are generally divided into two main approaches, namely the methods of Laspeyres IDA and Divisia IDA [19,20]. The main difference between the methods lies in their basic assumptions. The Laspeyres approach considers that when one aggregate value changes, other factors remain unchanged. Moreover, the Laspeyres framework is expressed as a percentage change. The Divisia approach, on the other hand, considers the change in factors over time and is expressed as logarithmic change. While the Laspeyres approach is easier to comprehend, it lacks precision and the representation of real change. The Divisia approach, on the other hand, is considered more scientific and reasonable [15,19].

The Divisia IDA method is further subdivided into the Arithmetic Mean Divisia Index (AMDI) method or the Logarithmic Mean Divisia Index (LMDI) method. The disadvantage of the AMDI method, which is based on the arithmetic mean, is that it produces a large residual value and cannot handle zero values. In contrast, the LMDI method that is based on logarithmic mean provides a perfect decomposition and provides techniques for dealing with zero values in the dataset. Furthermore, the LMDI method can be further divided into an additive and a multiplicative approach. The additive approach measures the change in quantitative volume, while the multiplicative approach measures the change as a proportion [15,19].

2.3. LMDI Decomposition Analysis in the Manufacturing Industry

Scientists around the world have conducted extensive research using the LMDI approach to conduct ex post analyses for changes in carbon dioxide emissions from global economies [15,16]. However, in recent years, only a few papers have been found that focus specifically on the manufacturing industry.

A study by [21] conducted a multisectoral decomposition analysis of CO_2 emissions in China's 22 economic sectors. The emission intensity effect was the main compensator for the growth of embodied carbon emissions in the sectors analyzed. The authors argued that international exports, which are strongly linked to economic growth, have the greatest impact on the increase in carbon emissions in the manufacturing sector. Therefore, effective policy measures should be taken to reconcile the rapid growth of exports with environmental sustainability in the long run [21].

A study by [22] combined Log-mean Divisia Index (LMDI) decomposition analysis with two-stage data envelope analysis (DEA) to analyze the drivers of change in energy consumption and carbon emissions of four sectors of BRI (Belt and Road Initiative) countries, namely (1) agriculture, fisheries, and forestry; (2) manufacturing; (3) transport; (4) other sectors. To measure changes in energy efficiency, indicators such as energy intensity, economic structure, labor productivity, and labor market were used as input parameters in DEA. To measure changes in CO_2 emissions, indicators such as emission intensity, energy structure, population, and energy consumption per number of inhabitants were used in DEA. The results show that energy intensity and labor market productivity have the largest impact on the increase in total energy consumption, while emission intensity and population trends influence most changes in aggregate CO_2 emissions. The study concludes that economic growth and activity factors have a significant impact on both energy consumption and the CO_2 emissions generated. Developed countries have higher levels of eco-efficiency, but should focus more on improving the environmental sustainability of the manufacturing sector [22].

Another study [23] used the LMDI decomposition of the multiplicative approach to analyze the changes in CO_2 emissions and carbon intensity in the Thai manufacturing sector over a 12-year period. The results showed that while the structural shift to manufacturing sectors with lower carbon intensity contributed significantly to the reduction of CO_2 emissions, increasing energy intensity and production volume increased both total emissions and emission intensity in manufacturing. The authors pointed out that more stringent policy measures should be taken to reduce energy intensity in Thailand's manufacturing sector. Otherwise, the economic benefits of industrial growth will be offset by a larger increase in emissions generated, with negative implications for long-term sustainability [23].

The importance of energy efficiency in manufacturing sectors was highlighted in a study by [24]. The authors applied LMDI decomposition analysis to examine whether national policies aimed at reducing emissions intensity in industry have led to reductions in CO_2 emissions in 28 subsectors of China's manufacturing industry over a 15-year period. The results show that both the effect of industrial activity and the effect of energy intensity are the main drivers of the increase in CO_2 emissions. It is important to consider sectoral heterogeneity, as larger reductions in CO_2 emissions can be achieved through tailored policies targeting high carbon intensity sectors. The authors recommend that governments increase investment in industrial technology development by introducing policy instruments that encourage manufacturing firms to adopt energy-saving measures, as energy efficiency is the most important factor in reducing overall emissions in industry [24].

A study by [25] came to similar conclusions. The study focused on examining changes in CO_2 emissions from six highly energy-intensive sectors in China, which together consume 90% of total industrial energy consumption. The results of the LMDI decomposition analysis show that over the period from 1986 to 2013, the rapid increase in industrial activity was the main driver of the increase in carbon emissions. Energy efficiency is the largest contributor to the decline in CO_2 emissions, with the chemical and non-metal manufacturing subsectors being particularly affected. Compared to other factors, structural changes and changes in the energy mix had a relatively smaller impact on the changes in CO_2 emissions in industry. The authors put forward number of policy recommendations to reduce both total industrial energy consumption and the CO_2 emissions generated. It is assumed that promoting industrial agglomeration will lead to large energy savings. In the past, mergers and acquisitions of large industrial companies producing steel and iron products have led to more efficient large-scale production. Therefore, the consolidation of energy-intensive companies should be encouraged in the future in order to achieve the climate targets in the manufacturing industry. In addition, the authors argue that technological advancement in this industry should be significantly accelerated. Although the results showed significant improvements in reducing the overall energy intensity of manufacturing, the pace of improvement was not fast enough to compensate the impact of industrial activity that increased emissions. Therefore, more incentives are needed for manufacturing companies to adapt advanced technological solutions that will lead to significantly higher energy savings. Moreover, the study concludes that governments should use fiscal instruments to encourage the restructuring of the energy mix of energy-intensive industries that are currently dependent on high fossil fuel consumption. Clean energy should be made more attractive by using policy instruments such as taxes or subsidies to encourage the transition to low-carbon systems in companies [25].

A study by [26] applied extended LMDI decomposition analysis to study how CO_2 emissions in China's manufacturing industry have changed in the period from 1995 to 2015. Fifteen manufacturing subsectors are included in the decomposition model that represents the overall structure of industry. The changes in total CO_2 emissions of the manufacturing industry are decomposed by eight different indicators, such as CO_2 emission factor of a particular fuel, energy mix, total energy consumption, production volume per unit of R&D expense, R&D investment per level of fixed asset investment, level of fixed assets, and share in value added. The authors conclude that sectors with high emissions and high energy intensity, such as the production of ferrous metals, chemicals, and non-metallic minerals, account for the largest share of total industrial emissions. The authors argued that the differences between subsectors have a significant impact on the achievement of overall industrial climate targets and should, therefore, be taken into account by policy makers. The increase in industrial activity over the period studied was the main factor that increased carbon emissions, while the effect of energy intensity was the main offsetting factor that decreased emissions. The results show that investment intensity was also an important factor in the increase in carbon emissions. However, investment in research and development played a crucial role in reducing CO_2 emissions in the manufacturing sector [26].

A research paper by [5] used the LMDI decomposition to analyze how technological progress and economic growth have influenced changes in greenhouse gas (GHG) emissions in Canadian industry from 1990 to 2014. The study found that the shift to less carbon-intensive industries and cleaner energy has contributed greatly to the reduction in GHG emissions. However, the effect of industrial activity was the main dominant effect driving the overall increase in GHG emissions in industry during the period analyzed. Based on the results of the decomposition analysis, the authors set out three policy recommendations, each targeting the main contributors to LMDI. First, eco-efficiency should be significantly promoted, and therefore, more aggressive policies should be adopted that promote the transition to carbon-neutral energy systems while supporting stable economic growth. Second, industry-specific requirements that set concrete benchmarks for energy and emissions intensity are necessary to promote energy efficiency in industry. Third, the government should continue to support policies that promote clean energy by phasing out fossil fuels and carbon-intensive energy sources such as coal in power generation [5].

To summarize, a study by [27] was one of the first to propose and formulate a decomposition analysis model for industrial energy efficiency and decarbonization analysis. This study applied the LMDI method and determined that changes in the total industrial energy consumption are measured by three main factors—the activity effect, structure effect, and energy intensity effect. To assess changes in industrial carbo emissions two additional factors are added to energy consumption decomposition analysis. As a result, changes in industrial carbon emissions are measured by five main factors—the activity effect, structure effect, energy intensity effect, energy mix effect, and emission factor effect [27]. Numerous studies have followed the approach introduced by [27] to decompose industrial carbon emissions—[28] for China's industrial sector, [29] for the Korean manufacturing sector, [30] for the Turkish manufacturing industry, [5] for the Canadian industrial sector, and [31] for the Mexican industry. However, no such study has yet been performed in Latvia. Given its sound theoretical basis and proven practical applicability, as well as the in-depth analysis and valuable findings found in previous studies applied in other countries, the model developed in this study is based on the framework introduced by [27], which uses the same factors to decompose energy-related carbon emissions from industry.

3. Methodology

Total energy-related CO_2 emissions in the manufacturing industry is determined as a sum of energy-related CO_2 emissions of each industrial sub-sector. The manufacturing sub-sectors are selected according to the classification nomenclature NACE Rev. 2 and grouped according to the statistical subdivision of the industrial sector [32]. Energy-related

CO_2 emissions in industry are decomposed according to Equation (1). The following steps for decomposing industrial energy-related CO_2 emissions are based on the equations and procedures demonstrated in the studies by [5,27]. The LMDI decomposition analysis indicators for industrial energy-related CO_2 emissions are summarized in Table 1.

$$C = \sum_{ij} C_{ij} = \sum_{ij} Q \frac{Q_i}{Q} \frac{E_i}{Q_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} = \sum_{ij} Q S_i I_i F_{ij} M_{ij} \quad (1)$$

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}—emission factor.

Table 1. LMDI decomposition analysis indicators for industrial energy-related CO_2 emissions.

Indicator	Notation	Time Period	Variable	Explanation	Data Source
Activity effect	*Act*	1995–2019	Aggregated industrial value added ($\sum_i EUR_i$) *	Measures changes in the growth of the total production output	[33,34]
Structural effect	*Str*	1995–2019	Share of production output of a subsector in the total industrial production ($EUR_i / \sum_i EUR_i$) *	Measures the level of restructuring in industry by shifting to less energy-intensive sectors	[33,34]
Energy intensity effect	*Int*	1995–2019	The amount of energy consumed per unit of production output (GWh_i/EUR_i) *	Measures the level of energy efficiency improvement	[34,35]
Fuel mix effect	*Fuel*	1995–2019	Share of energy consumption of non-renewable energy products ($E_{ij} / \sum_i E_i$)	Measures the decarbonization effect of the industry	[35]
Emission intensity effect	*Emi*	1995–2019	Emission intensity of consumed energy resources (tCO_2/GWh) *	Measures the emissions intensity of the fuel mix	[36]

* chain-linked volumes of base year 2015.

A subscript *i* denotes the representative value of a subsector; the absence of a subscript *i* represents the total value of the industry. A subscript *j* denotes the type of energy product in the total energy balance, e.g., natural gas, electricity, biofuels, and others. S_i ($=Q_i/Q$) and I_i ($=E_i/Q_i$) are the levels of production activity and energy intensity of each industrial subsector, and thus, they represent the structural and energy intensity effects. F_{ij} ($=E_{ij}/E_i$) represents the fuel mix of a sector and M_{ij} ($=C_{ij}/E_{ij}$) the emission factor of a particular fuel in the overall energy balance.

Since change in the aggregate level of C changes from initial year 0 to year T, then generated CO_2 emissions in a base year $E^0 = \sum_i Q^0 S_i^0 I_i^0 F_{ij}^0 M_{ij}^0$ and $E^T = \sum_i Q^T S_i^T I_i^T F_{ij}^T M_{ij}^T$. The effect of each component is determined using LMDI I additive decomposition analysis technique, according to Equation (2), which was chosen for its ability to measure the absolute change in CO_2 emissions and the ease of interpreting the results:

$$\Delta C = C^T - C^0 = \Delta C_{act} + \Delta C_{str} + \Delta C_{eni} + \Delta C_{fuel} + \Delta C_{emi} \quad (2)$$

where:

act—effect from changes in industrial activity;
str—effect from changes in structure;
eni—effect from changes in energy intensity;

fuel—effect from changes in fuel mix;
emi—effect from changes in emission intensity.

Each effect is further expressed in Equations (3)–(7):

$$\Delta C_{akt} = \sum_{ij} \frac{C_{ij}^{T} - C_{ij}^{0}}{lnC_{ij}^{T} - lnC_{ij}^{T}} ln \frac{Q^{T}}{Q^{0}} \tag{3}$$

$$\Delta C_{str} = \sum_{ij} \frac{C_{ij}^{T} - C_{ij}^{0}}{lnC_{ij}^{T} - lnC_{ij}^{T}} ln \frac{S_{i}^{T}}{S_{i}^{0}} \tag{4}$$

$$\Delta C_{eni} = \sum_{ij} \frac{C_{ij}^{T} - C_{ij}^{0}}{lnC_{ij}^{T} - lnC_{ij}^{T}} ln \frac{I_{i}^{T}}{I_{i}^{0}} \tag{5}$$

$$\Delta C_{fuel} = \sum_{ij} \frac{C_{ij}^{T} - C_{ij}^{0}}{lnC_{ij}^{T} - lnC_{ij}^{T}} ln \frac{F_{ij}^{T}}{F_{ij}^{0}} \tag{6}$$

$$\Delta C_{emi} = \sum_{ij} \frac{C_{ij}^{T} - C_{ij}^{0}}{lnC_{ij}^{T} - lnC_{ij}^{T}} ln \frac{M_{ij}^{T}}{M_{ij}^{0}} \tag{7}$$

where:
E^{T}—energy consumption in future year T;
E^{0}—energy consumption in initial year.

Data utilized in this study were collected from the Eurostat and Central Statistical Bureau of Latvia (CSB) databases [33–35]. For industrial energy consumption, data on the final consumption of each industrial subsector were used. Chain-linked values of value-added data were used in order to consider possible variations in the data due to price changes affecting the representation of industrial output produced. Data on emission factors for utilized fuels were taken from IPCC guidelines for national greenhouse gas inventories on default emission factors for stationary combustion in manufacturing industries and construction [36]. Emission factors were converted from TJ to MWh, using the conversion factor of 277.78. Table 2 summarizes the emission factors of fuels used in the decomposition analysis.

Table 2. Emission factors of fuels.

Fuel Type	Emission Factor, tCO_2/MWh
Anthracite	0.354
Other bituminous coal	0.341
Coke oven coke	0.385
Natural gas	0.202
Gas oil and diesel oil	0.267
Fuel oil	0.279
Other oil products n.e.c.	0.264
Renewables and biofuels	0
Peat	0.382
Liquefied petroleum gases	0.227
Motor gasoline	0.249
Other kerosene	0.259
Lignite	0.364
Petroleum coke	0.351
Non-renewable waste	0.330
Kerosene-type jet fuel	0.257

The data for CO_2 emission factor for electricity produced in Latvia were collected from the European Environment Agency [37]. The CO_2 emission factor for heat produced in heat plants and combined heat and power plants in Latvia was calculated according to the Equation (8), which was obtained from Cabinet Regulation No. 42. of the Republic of Latvia "Methodology for Calculating Greenhouse Gas Emissions" [38]:

$$C_{heat} = \frac{\sum\left(Q_{th\ (fossil)} \cdot C_{fuel}\right)}{Q_{th}} \tag{8}$$

where:

C_{heat}—CO_2 emission factor for heat produced in heat plants and combined heat and power plants in Latvia, tCO_2/MWh;
$Q_{th\ (fossil)}$—amount of produced heat in heat and CHP plants in Latvia using fossil fuels;
C_{fuel}—emission factor of the utilized fuel according to the Appendix 1 of the Cabinet Regulation No. 42.

The data for the calculations were obtained from the Central Statistical Bureau of Latvia [39,40]. Data on produced heat in heat and CHP plants in Latvia and utilized fuel included the values for the time period from 2012 to 2019. Since the scope of the decomposition analysis included the historical data analysis for the time period from 1995 to 2019, the emission factor for heat for the years from 1995 to 2012 was assumed to be equal to the emission factor of natural gas, taking the value 0.202 tCO_2/MWh. This should be considered as a limitation of the study; however, it has a low impact on the overall results.

4. Results and Discussion

4.1. Manufacturing Industry Description

4.1.1. Total Energy Consumption and CO_2 Emissions in Latvian Manufacturing Industry

A historical data analysis of the Latvian manufacturing sector shows that in the period from 1995 to 2019, the total CO_2 emissions in the industry decreased by 41%. Figure 1 illustrates the aggregated values of total energy consumption and CO_2 emissions of the Latvian manufacturing industry. However, while the overall trend is downward, the total CO_2 emissions have fluctuated over the years. The largest decreases were observed in the period from 1995 to 2000. A large drop in the period is explained by the significant decrease in the consumption of coal (−11%), peat (−100%), oil and petroleum products (−39%), and heat (−67%) in 2000 compared to 1995 levels. The decrease in fossil fuel consumption was offset by the increase in renewable energy and biofuels, which increased by 16% over this period. The second largest decrease in CO_2 emissions was observed during the period of the global financial crisis, when total CO_2 emissions decreased by 21% in 2009 compared to 2008. However, after the financial crisis, CO_2 emissions increased back to the original level and then gradually decreased on an annual basis until 2017. CO_2 emissions data in recent years show that a significant increase in CO_2 emissions was observed in 2018, when emissions increased by 31% compared to 2017. Therefore, more attention should be paid to investigating the possible sustainability and energy efficiency gaps in the Latvian manufacturing industry in recent years.

Regarding the distribution of energy consumption between sectors, it can be noted that a significant structural change has taken place in this sector in the last decade. The manufacturing sector in Latvia experienced a significant structural change in the period from 2000 to 2019, as after the bankruptcy of the largest metal producer, the share of iron and steel in total energy consumption decreased from 25% in 2000 to 0.13% in 2019. However, a huge increase was achieved by the wood and wood products sector (44 percentage points) and the non-metallic minerals sector (8 percentage points). In 2019, the three largest manufacturing sectors in Latvia—wood processing (5676 GWh), non-metallic minerals production (1888 GWh) and food processing (907 GWh)—consumed 89% of the total manufacturing energy consumption.

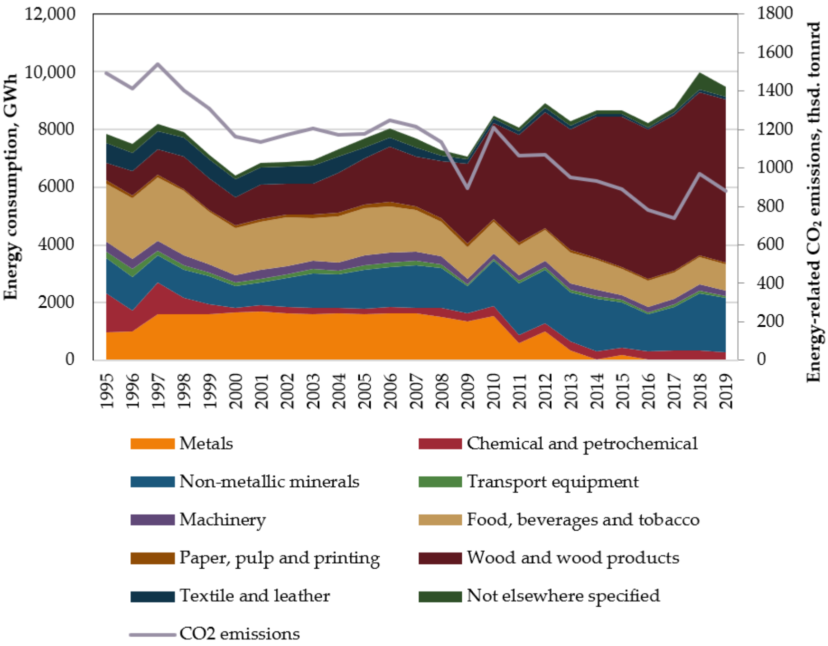

Figure 1. Energy consumption of the Latvian manufacturing industry.

There are differences between the sectoral contributions to total energy consumption and the total CO_2 emissions generated. Figure 2 shows the cumulative contribution to the total CO_2 emissions of the manufacturing industry. The non-metallic minerals production sector produced the highest amount of total CO_2 emissions in 2019, accounting for 46% of the total CO_2 emissions generated by the Latvian manufacturing sector. The second largest emitter was the wood processing sector, which produced 27% of the total CO_2 emissions of the manufacturing sector in 2019, followed by the food processing sector, which produced 15% of the total CO_2 emissions of the manufacturing sector. The impact of structural change in the period from 2010 to 2015 was also observed for the CO_2 emission distribution of the Latvian manufacturing sector. In 2010, the metal processing sector in Latvia accounted for a quarter (25%) of total emissions, while in 2015, it accounted for only 3%. A sharp decrease in the share of the metal sector in total CO_2 emissions changed the overall CO_2 emission distribution between sectors in the following years. The highest increase in the share of CO_2 emissions was observed in the wood processing (+15 pp and non-metallic mineral production (+10 pp) sectors.

The amount of CO_2 emissions generated by the sector is highly dependent on the overall fuel mix used for combustion and the overall production processes of the sector. Figure 3 shows the fuel mix for each manufacturing subsector and presents the average values for the period 2015–2019. Significant differences between sectors can be observed. Part of the explanation behind higher generated CO_2 emissions by the non-metallic mineral sector can be explained by the fact that the sector consumes a considerable amount of solid fossil fuels, non-renewable waste, and natural gas, which each individually possess high emission factors. The wood processing sector stands out with the highest share of renewables, where biomass accounts for 80% of the total consumed energy products. The advantage of wood processing sector is that one of the main production byproducts are wood residues and wood chips, which can later be utilized for the combustion process. The metals sector (59%), textile and leather sector (54%), paper, pulp, and printing sector (45%), food processing sector (41%), and chemicals and petrochemical sector (38%) each consume considerable amounts of natural gas accounting for a substantial share of the subsector's total energy mix. The transport equipment manufacturing sector stands out as the most electricity-intensive compared with other subsectors. Electricity accounts for 57% of the total energy consumption in the transport equipment manufacturing sector. High electricity consumption is also observed in the paper, pulp, and printing sector (46%) and machinery sector (47%) where electricity accounts for almost half of the total energy consumption in the representative sectors.

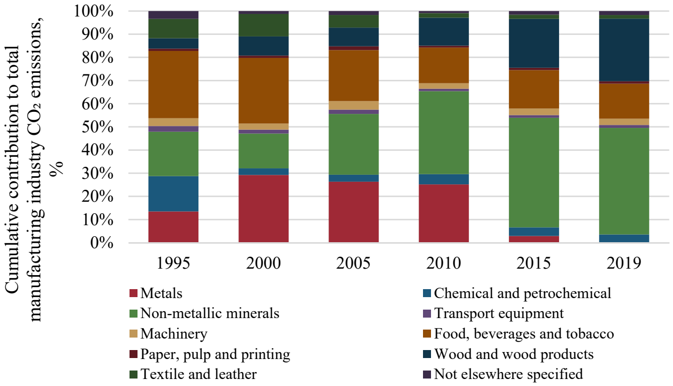

Figure 2. Cumulative contribution of CO_2 emissions by sector.

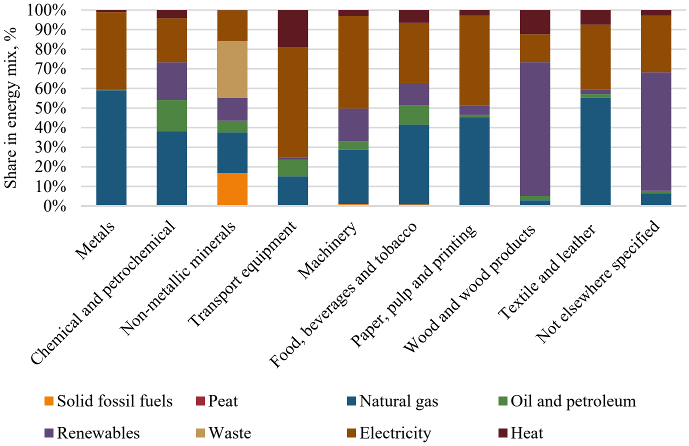

Figure 3. Fuel mix of manufacturing sub-sectors.

4.1.2. Energy and CO_2 Emission Intensities

In order to examine the specifics of energy consumption patterns of each sector and make comprehensive comparison between the sectors, energy and emission intensities are calculated for each subsector. According to the obtained values sectors are classified into three groups—high, medium, and low intensity, as illustrated in Figures 4 and 5. The energy intensity indicator is expressed as the ratio between energy consumed in the sector (GWh) and value added generated in chain-linked volumes (MEUR).

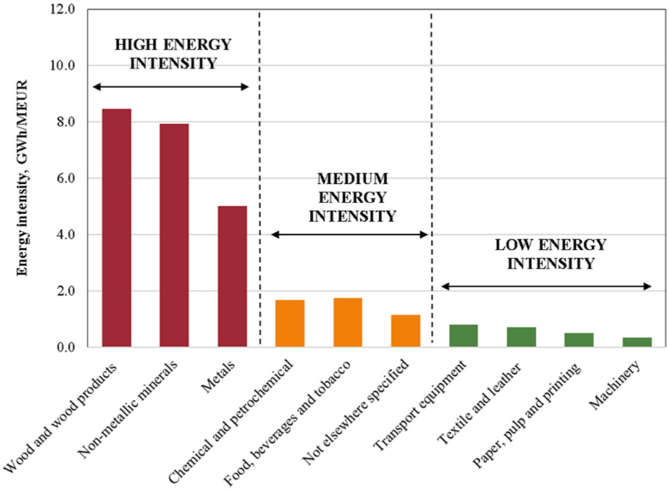

Figure 4. Energy intensities of Latvian manufacturing industry sectors.

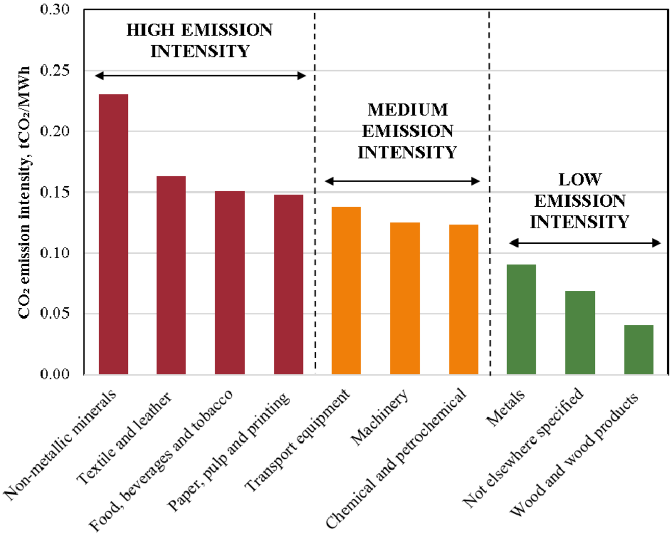

Figure 5. Emission intensities of Latvian manufacturing industry sectors.

High energy intensity group included three sectors—wood processing (8.45 GWh/MEUR), non-metallic mineral production (7.94 GWh/MEUR), and metals manufacturing (5.02 GWh/MEUR). The energy intensity values of the medium intensity group are on average five times lower than for the high energy intensity group. Moreover, low energy intensity group values are on average almost twelve times lower than high intensity and three times lower than medium intensity group values. Medium energy intensity group also included three sectors—chemical and petrochemical (1.74 GWh/MEUR), food, beverages, and tobacco (1.69 GWh/MEUR), and other or not elsewhere specified sectors (1.15 GWh/MEUR). Low energy intensity group included four sectors—transport equipment (0.81 GWh/MEUR), textile and leather (0.72 GWh/MEUR), paper, pulp, and printing (0.51 GWh/MEUR), and machinery (0.35 GWh/MEUR).

From the assessment of energy intensity and grouping, it can be concluded that the production of basic goods and raw materials such as wood products, building materials, and metals requires high energy input and the goods produced are not realized at high prices. Therefore, the overall ratio of energy consumption to value added generated is much higher in these sectors than in sectors that produce higher value-added final goods that can be realized at a much higher selling price. Wood, non-metallic minerals, and metal products are usually not an end product in the overall production supply chain, but an important raw material that is further used for the assembly of the higher value final product. On the contrary, high value-added sectors such as machinery and transport equipment show low energy intensity, since these sectors produce end products that are usually sold at significantly higher prices due to their production complexity, which requires high knowledge intensity.

The emission intensity indicator is expressed as the ratio between the generated energy-related CO_2 emissions and the consumed energy resources (tCO_2/MWh). Figure 5 shows the emission intensity values for each subsector. Similarly, as was shown in the energy intensity analysis, the emission intensity values were grouped according to high, medium, and low emission intensities.

The high emission intensity group include four sectors—the non-metallic mineral production sector (0.23 tCO_2/MWh), textile and leather production sector (0.16 tCO_2/MWh), transport equipment manufacturing sector (0.15 tCO_2/MWh), and paper, pulp, and printing manufacturing sector (0.15 tCO_2/MWh). The high emission intensity in these sectors can be explained by the energy mix used, as described above. All these sectors have the lowest concentration shares of renewables in the overall fuel mix and natural gas is a strong component in the overall energy balance of these sectors.

The medium emission intensity group include four sectors—the food processing sector (0.14 tCO_2/MWh), machinery manufacturing sector (0.13 tCO_2/MWh), and chemical and petrochemical manufacturing sector (0.12 tCO_2/MWh). Low intensity group sectors possess on average three times lower emission intensity than for the high emission group and two times lower emission intensity than for the medium emission intensity group. The low emission intensity group include three sectors—the metals manufacturing sector (0.09 tCO_2/MWh), other or not elsewhere specified sectors (0.07 tCO_2/MWh), and wood processing sector (0.04 tCO_2/MWh). Wood processing and other sectors contain the highest share of biomass in the overall energy mix, which explains the substantially lower emission intensity compared to other sectors.

4.2. Decomposition Analysis Results

Measures to save carbon dioxide emissions in the manufacturing industry are particularly challenging, as the sector faces a constant struggle between economic growth drivers and sustainability issues [3]. Decomposition analysis have been constructed for Latvian manufacturing industry to monitor changes in total industrial CO_2 emissions over the period from 1995 to 2019 determined by five main factors—the industrial activity effect, structure effect, energy intensity effect, fuel mix effect, and emission intensity effect. The study period was divided in five groups, each accounting for a 5-year time interval, except for the last group, which represents the time period from 2015 to 2019 and, thus, includes a 4-year time interval. Since there were no data on 2020 yet available, year 2019 values were the latest available data that were included in the study. Figure 6 shows the results of the decomposition analysis in combination with the CO_2 growth rates during the representative period.

The overall CO_2 growth rate in the Latvian manufacturing industry have 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%. It can be concluded that CO_2 reduction in the manufacturing industry has stagnated in recent years, and there has been little improvement in the last 5 years. Furthermore, the fluctuations in the results show that the changes in CO_2 emissions are unsteady, so a more detailed study of the influencing factors should be conducted.

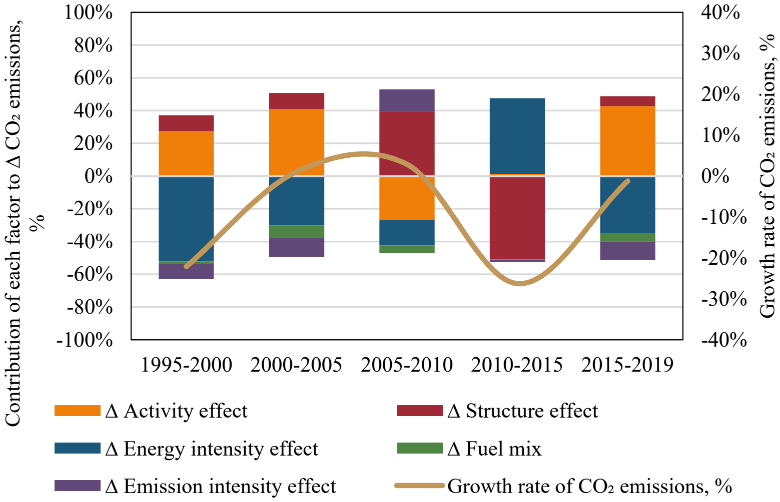

Figure 6. Aggregated decomposition analysis results for the time periods.

Table 3 summarizes the main decomposition results in total absolute values. Significant differences are observed between periods. In the first period (1995–2000), the main driver of changes in industrial CO_2 emissions was a decrease in energy intensity. This can be explained by the significant changes in the general economic restructuring and structure of the economy, when, after the restoration of independence in Latvia, the existing enterprises were forced to reorganize their original production methods and numerous new manufacturing companies entered the market. Therefore, significant investments were made and modernization measures were carried out in the manufacturing companies, which led to an increase in efficiency. In addition, the consumption of coal and petroleum products was significantly reduced during this period, which contributed to the overall reduction of CO_2 emissions.

Table 3. Decomposition analysis results in aggregated values for the determined periods.

	1995–2000	**2000–2005**	**2005–2010**	**2010–2015**	**2015–2019**
Δ Activity effect	353.1	336.8	−154.7	86.9	186.9
Δ Structure effect	123.9	81.4	225.3	−3242.6	26.5
Δ Energy intensity effect	−668.5	−248.8	−88.5	2956.1	−151.5
Δ Fuel mix	−19.5	−62.2	−27.0	−21.4	−23.3
Δ Emission intensity effect	−119.1	−95.0	78.8	−96.9	−49.4
Δ CO_2 emissions	−330.2	12.3	33.8	−317.8	−10.7

In the second period (2000–2005), an increase in CO_2 emissions from manufacturing industries was observed. In the first period, the main driver of changes in CO_2 emissions was the effect of industrial activity. Increasing demand in both local and export markets led to a significant increase in production volumes, which increased production capacity and drove the overall development of the industry. Improvements in energy and emissions intensity could not compensate for the effect of increasing industrial activity, so CO_2 emissions increased during this period.

In the third period (2005–2010), similar to what was observed in the second period, total CO_2 emissions increased by 33.8 thousand tons in absolute values and showed a 3%

CO_2 growth rate. The period is characterized as the period before the global financial crisis, when a general decrease in industrial activity was observed in all manufacturing subsectors. During this period, a significant shift to more energy-intensive sectors was observed.

The fourth period (2010–2015) shows a large decrease in CO_2 emissions. The period is characterized by a large significant restructuring that occurred due to the existence of the largest metal producer in the market. As the metal production sector accounted for 25% of the total CO_2 emissions of the manufacturing sector in the past, the bankruptcy of the largest player in the market subsequently affected the overall reduction of industrial CO_2 emissions. During this period, a large effect was also observed in the factor of energy intensity, which can be explained by the inefficiency of the production processes of the respective metal production company.

The fifth period (2015–2019), or the period representing the latest trends in the industry, showed a modest reduction in CO_2 emissions, where the total decreased in absolute terms by 10.7 thousand tons of CO_2 emissions and a negative growth rate of −1%. Although a significant improvement in energy efficiency and decarbonization measures can be observed, the effect from the improvements was largely offset by the increasing industrial activity. This suggests that the current pace of improvements may not be sufficient to achieve greater CO_2 emission reductions in industry in the future. Table 4 summarizes the main events during the analyzed time intervals that influenced the change in CO_2 emissions.

Table 4. Main events during the representative period driving change in CO_2 emissions.

Time Period	Main Events during the Representative Period Driving Change in CO_2 Emissions
1995–2000	Period after the restoration of independence during which the entire Latvian economy, including the manufacturing industry, was significantly restructured. Significant reforms in the form of ownership and changes in the foreign trade regime affected the overall development of manufacturing industry. Imported raw materials and energy resources were now subject to world market prices, which meant that some factories that had previously been successful due to low energy costs were no longer competitive in export markets. This forced manufacturing companies to redesign production processes and invest in energy efficiency measures.
2000–2005	The period before the financial crisis was mainly characterized by high economic growth and the increase in industrial production and energy consumption. Investments in the modernization of factories and in energy efficiency could not compensate for the effect of increasing activity, which drove up CO_2 emissions.
2005–2010	Period of the global financial crisis, during which a sharp decline in total production volumes was observed from 2006 to 2009. As a result, a significant reduction in energy consumption and emissions produced was achieved. However, in 2010, a sharp increase in industrial activity led to an increase in total CO_2 emissions during this period. A shift towards more energy intensive sectors was observed during this period. The entire industrial sector experienced a significant structural change.
2010–2015	Bankruptcy and market exit of the largest metal producer led to significant structural changes in the entire industry. The sudden decline in metal production was largely offset by the rapid expansion of the wood processing sector, which drove up energy consumption overall in the industry.
2015–2019	Higher economic growth and rising demand in the largest export markets led to an increase in production output and caused energy consumption to rise. Although there is a positive trend in the overall decarbonization of the fuel mix and reduction of the emission factor, the overall growth rate of CO_2 emissions shows an upward trend and reduction of CO_2 is stagnating.

Figure 7 illustrates year-to-year changes in the contribution of each decomposition factor to the changes in CO_2 emissions and the overall growth rate of CO_2 emissions with all subsectors included and Table 5 summarizes the results in absolute values. The growth rate of CO_2 emissions is negative and shows a fluctuation pattern. However, two significant peaks are observed in the periods from 2009 to 2010 and from 2017 to 2018. The first one is explained by the recovery of the manufacturing industry after the financial crisis. However, a more detailed investigation is carried out to explain the reasons for the second peak observed in recent years.

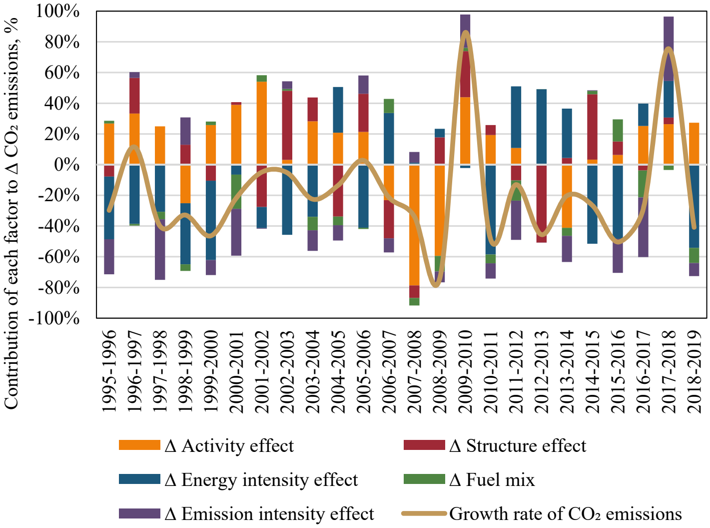

Figure 7. CO_2 emission decomposition results for the manufacturing industry.

Table 5. Aggregate year-to-year changes in decomposition factors and CO_2 emissions.

	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018	2018–2019
Δ Activity effect	58	24	−7	−30	42	17	49	66	55
Δ Structure effect	19	−23	−3787	3	545	24	−7	11	−1
Δ Energy intensity effect	−176	90	3677	24	−659	−133	29	59	−107
Δ Fuel mix	−17	−30	2	−4	28	40	−34	−9	−20
Δ Emission intensity effect	−30	−57	−2	−13	5	−61	−76	105	−17
Δ CO_2 emissions	−146	5	−117	−20	−40	−113	−40	232	−90

Over the period of ten years, the manufacturing industry experienced a shift from one energy intensive sector (metal manufacturing) to other 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, which 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 results prove that energy efficiency improvements are the most important strategy for the long-term development of companies to achieve energy and emission savings. 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 demand [6].

These findings are consistent with the decomposition results of the Odysee-Mure energy efficiency decomposition model for Latvian industry [41]. The Odysee-Mure energy consumption decomposition of industry for the period from 2000 to 2018 showed that the total energy consumption of industry increased by 2.5% annually in the studied period, which is mainly due to the increase in industrial activity in two important subsectors of Latvian industry—wood processing and non-metallic mineral production. The Odysee-Mure decomposition of energy efficiency in industry concludes that the improvements in energy efficiency, which enabled significant energy savings in industry and reduced the overall energy intensity of industry, contributed to the fact that total energy consumption did not increase even more [41].

In total, in the time period from 2015 to 2019, a larger decrease in energy intensity in the manufacturing industry was observed compared with the first half of the decade. Part of the explanation in energy efficiency activity in 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 from policies that might have stimulated larger energy savings and the achievement of more ambitious energy efficiency targets [34].

The results of the decomposition analysis showed that improvements in energy intensity have contributed most to reducing CO_2 emissions in the manufacturing sector in the past. Therefore, in order to observe how recent energy efficiency measures might have affected the green transformation in industry, a more detailed analysis is conducted for a period from 2015 to 2019. Figure 8 illustrates the contribution of each effect on changes in CO_2 emissions and overall change in generated CO_2 emissions in each sub-sector in the time period from 2015 to 2019.

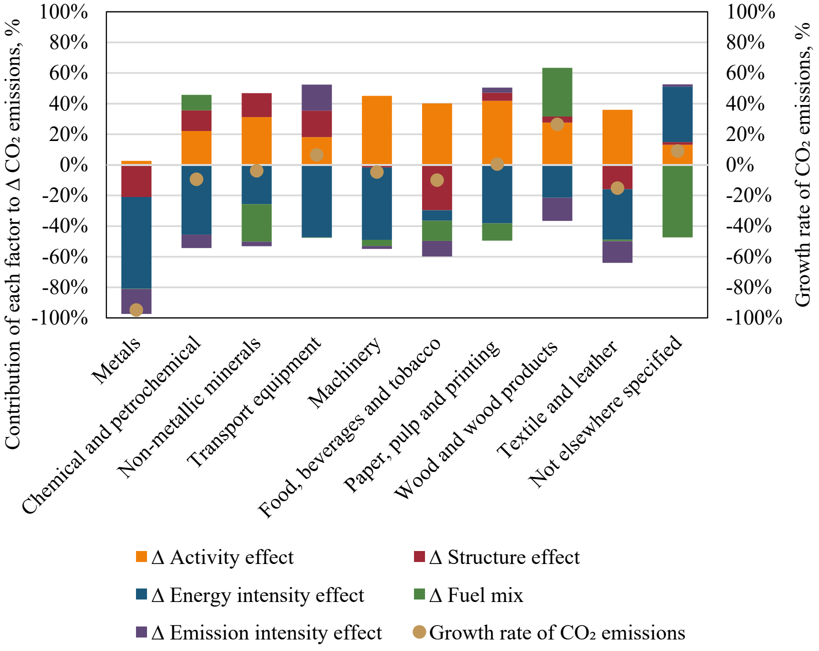

Figure 8. CO_2 emission decomposition for the time period from 2015 to 2019.

In total, in 2019, almost all manufacturing industry sub-sectors indicated a reduction in CO_2 emissions compared to the levels of year 2015. However, three sectors reported the opposite. In 2019, CO_2 emissions increased by 6% in transport equipment production sector, by 26% in wood processing sector, and by 9% in other sub-sectors compared to 2015.

The energy intensity effect was the main driver that contributed to the reduction of CO_2 emissions in most of the sectors, except for not elsewhere specified sectors (plastics, rubber, furniture, and other manufacturing) in the period of the last five years. 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, total rise in industrial activity, structural effect, and fuel mix effect counteracted the energy intensity effect. Therefore, the current energy efficiency improvements could not compensate these effects, which drove up the overall CO_2 emissions at a much higher pace than the implemented energy efficiency measures.

The structural effect shows the overall change in the contribution of a particular sector to the total industrial activity. That is, if the structural effect is positive, then the total industrial activity in the sector has increased as has the total contribution to the total industrial value added. On the other hand, a negative value means that the sector's contribution to the total value added generated has decreased. The results show that the share of metals production sector, food processing sector, and textile production sector in the total industrial generated value added has decreased. This structural effect also contributed to the achievement of higher CO_2 reductions in the sector. On the contrary, the chemicals production sector, non-metallic mineral production sector, and transport equipment production sector has raised their contribution to the overall generated industrial added value over the period from 2015 to 2019.

Year-to-year changes in CO_2 emissions were examined in more detail for the largest manufacturing sector in Latvia—wood processing, which alone consumes almost two-thirds of all industrial energy use in Latvia. Figure 9 illustrates the results of the CO_2 emission decomposition for the wood processing sector.

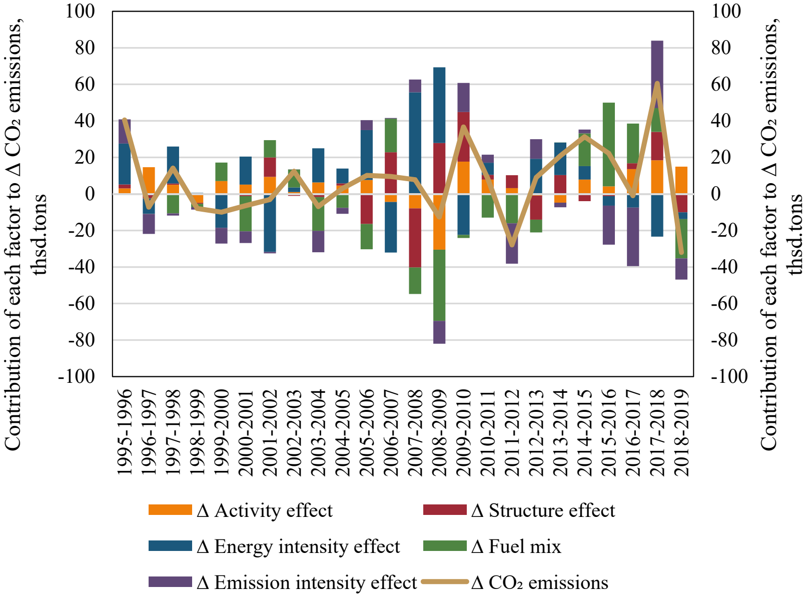

Figure 9. CO_2 emission decomposition results for the wood processing sector (C16).

Industrial activity was the main reason for the sharp increase in the total energy consumption of the wood processing sector during the studied period. 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 [6]. The influence of export demand on industrial manufacturing activity and its embodied carbon emissions was demonstrated in the study of [21], where a decomposition analysis of manufacturing CO_2 emissions in China showed that the growth of international exports of produced goods had the greatest influence on the increase in industrial CO_2 emissions [21]. Similarly, Latvia's wood processing sector has seen exports increase by 82% in the last decade (over the period 2010–2019) [42] 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 [33].

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 the total fuel mix, signaling 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 overall demand for wood products, particularly wood pellets 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.

Figure 10 illustrates the changes in the total distribution of energy products consumed in the wood-processing sector during the last five years. The change index shows the amplitude of how the consumption of certain products has changed compared to the values of 2015, which is taken as the base year. In general, it can be observed that the demand for heat has more than doubled; additionally, the consumption of oil products, natural gas, and electricity has gradually increased. However, the consumption of wood products has decreased. Therefore, the results indicate that there is an overall negative trend towards higher consumption of fossil energy resources.

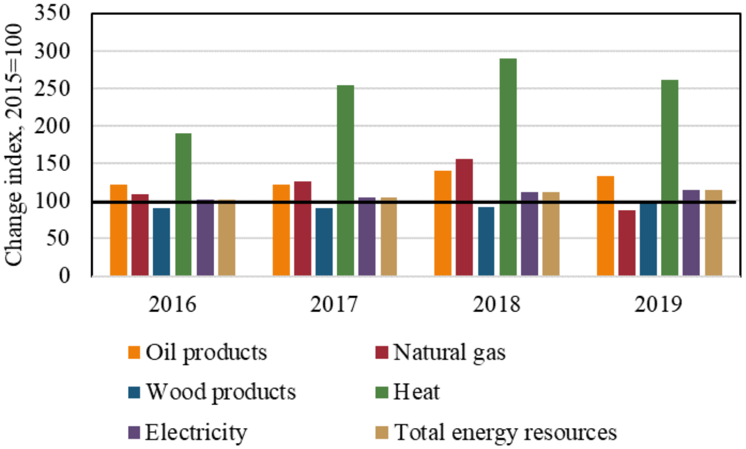

Figure 10. Changes in the energy balance of the wood processing sector (C16).

Subsequently, this trend affects both the overall share of RES in the total fuel mix and the emission intensity of the sector, as shown in Figure 11. It can be observed that the total share of wood products in the total fuel mix gradually decreased except in 2019. As a result, the emission intensity indicator fluctuates in the representative years. A significant peak in emission intensity is observed in 2018, when the share of RES in the total fuel mix reached the lowest value.

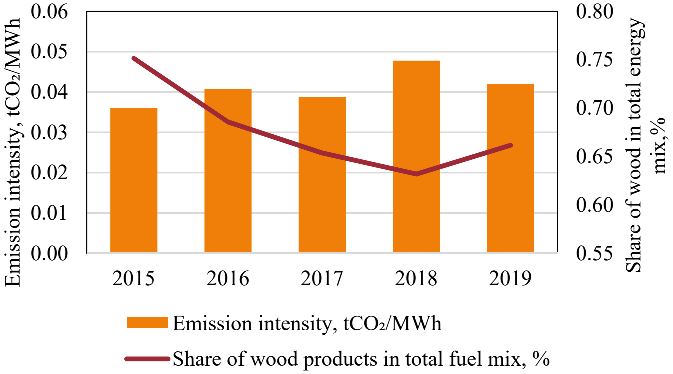

Figure 11. Changes in emission intensity and share of RES in the wood processing sector (C16).

In addition, a correlation analysis was performed to investigate the relationship between the volumes of wood products produced and the RES share in the energy balance of the wood processing sector, as shown in Figure 12. The results for the period from 2013 to 2019 show a strong correlation (R^2 = 0.9059), with a downward slope between the two variables. The correlation analysis confirms that the increase in industrial activity in the wood processing sector caused the share of RES to decrease. The exception of 2019 can be explained by the fact that in 2019 in Latvia was observed a winter with mild temperatures; therefore, there was also a lower demand for wood products, including pellets.

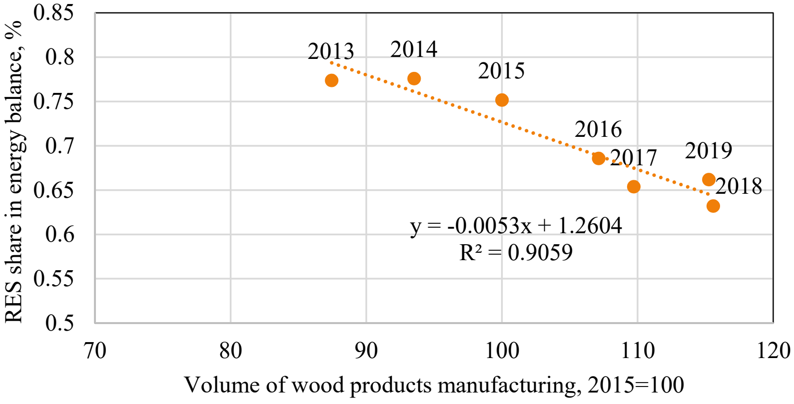

Figure 12. Correlation analysis between wood production amounts and share of RES.

5. Conclusions and Policy Recommendations

In this study, an ex-post assessment of industrial energy-related CO_2 emissions were carried out. The Log-Mean Divisia Index (LMDI) decomposition analysis method was applied to decompose changes of industrial energy-related CO_2 emissions based on five main drivers, i.e., the industrial activity effect, structural change effect, energy intensity effect, fuel mix effect, and emission intensity effect. Decomposition analysis results showed that although there is a significant improvement in energy efficiency and decarbonization measures in the industry, the effect from the improvements has been largely offset by increasing industrial activity. In this paper, the relationship between economic growth and climate change measures was demonstrated. The rapid growth of industrial production activity, especially in energy-intensive sectors such as the wood processing sector, will require a much greater improvement in industrial energy efficiency in the future. The results of this study confirm that energy efficiency measures have the greatest impact on reducing carbon emissions in industrial companies.

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 industrial energy policy, as suggested in the study by [5]. Specific regulations and climate targets for each sector would make it possible to identify underperforming companies and develop tailored measures to promote decarbonization and energy efficiency in companies. Therefore, quantifying and monitoring energy efficiency targets specifically for each industrial subsector are the priority to realize the untapped energy efficiency potential of Latvian industry [5].

The results of this study suggest that 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. Encouraging investment in R&D was highlighted as a critical policy measure in the studies by [28,43], who examined the key drivers of changes in industrial carbon emissions and used the findings to develop recommendations to promote deep decarbonization in industry. Investment in R&D provides more opportunities for the development and adaptation of energy-saving technologies and the further development of technological solutions for energy conservation and clean energy adaptation, which bring both economic and environmental benefits to industrial enterprises [28,43]. The government should develop policy instruments to support R&D activities in industry. 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. As both wood processing and non-metallic minerals production require large amounts of heat for production processes, the installation of heat recovery systems in companies, especially in large industrial plants, could lead to CO_2 savings of up to 35% [44]. Therefore, the government should support the adaptation of heat recovery technologies by providing financial incentives that would reduce the overall payback period of these technologies.

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 [25]. Phasing out of carbon-intensive energy sources could be achieved by making their price less attractive and renewable energy sources more affordable for businesses [5,25].

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Nomenclature

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}	emission factor
i	representative value of a subsector
j	the type of energy carrier in the total energy balance
act	effect from changes in industrial activity
str	effect from changes in structure
eni	effect from changes in energy intensity
fuel	effect from changes in fuel mix
emi	effect from changes in emission intensity
E^T	energy consumption in future year T
E^0	energy consumption in initial year

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PAPER 3: THE STATUS QUO OF THE EU TRANSPORT SECTOR: CROSS-COUNTRY INDICATOR-BASED COMPARISON AND POLICY EVALUATION

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The status quo of the EU transport sector: Cross-country indicator-based comparison and policy evaluation[☆]

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HIGHLIGHTS

- Transport decarbonization depends largely on the effectiveness of national policies.
- Energy savings and switching to RES have difficulty offsetting economic growth impact.
- Most countries lag behind in providing the infrastructure for zero-emission vehicles.
- Different mechanisms should be used in Nordic, Western, and Eastern EU countries.

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ABSTRACT

Greenhouse gas (GHG) emissions are declining in all major sectors in the European Union, with the exception of one sector that has seen a significant increase in GHG emissions over the past decade - transport sector. The European transport sector faces a significant challenge in achieving the decarbonization goal set by the European Green Deal. Although the European Commission is planning to introduce a set of EU-level measures, such as the inclusion of road transport in the EU Emissions Trading System, the progress of greening the transport sector has so far largely depended on national policies. To understand whether European countries are committed to rapidly adapt to low-carbon transport systems, it is crucial to evaluate what progress have national policies achieved so far in moving towards a sustainable transport system. This study used a three-level assessment of transport sector sustainability across European countries. First, this study assessed the overall sustainability level of the transport sector in all European Union Member States 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 obtained from Eurostat, European Commission, and Odysee-Mure databases. Second, in order to identify the dynamics of progress, Logistic Mean Division Index (LMDI) decomposition analysis was conducted to assess the changes in greenhouse gas (GHG) emissions from the transport sector over ten years, taking into account the five main factors: emission intensity effect, renewable energy (RES) transition effect, energy intensity effect, economic growth effect, and population growth effect. Third, to analyse what has impacted the sustainability of the transport sector in countries, the study highlighted several key policies (directions) for decarbonizing transport from the analysis outlining the good practice policies from the best performing countries. The combined results of the composite sustainability index and decomposition analysis revealed significant differences between Nordic, Western, and Eastern European countries, suggesting that different approaches should be taken in developing effective sustainability policies for transport.

1. Introduction

The transport sector is one of the largest polluters and contributors to climate change globally and in the European Union. Greenhouse gas (GHG) emissions from the transport sector account for almost a third of total GHG emissions in the EU. More importantly, in just two decades,

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[☆] The short version of the paper was presented at ICAE2021, Nov 29 - Dec 5, 2021. This paper is a substantial extension of the short version of the conference paper.

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GHG emissions from the transport sector in the EU increased by 24 % in 2019 compared to 2000 [1]. While most other sectors of the economy (buildings, industry, energy) and the EU in general have seen a decrease in GHG emissions levels, GHG emissions from the transport sector are well above 1990 levels [2,3]. As a result, the transport sector's growth, which requires higher energy demand and drives up GHG emissions, is currently occurring at the expense of realized energy efficiency efforts by other sectors that have succeeded in gradually reducing their energy and emissions intensities [4].

The lack of adaptation of sustainable policies, innovations, and stringent measures in the transport sector has led to an annual increase in GHG emissions. It shows that no progress has been made in achieving climate neutrality targets [3]. Therefore, the transport sector is now considered one of the most critical cornerstones in achieving the ambitious Paris Agreement commitments and targets of European Green Deal [5]. The urgency of the EU's transport sector decarbonization was also addressed in the context of strengthening the EU's energy independence. The transport sector is among the highest dependencies on fossil fuels [6], which are not only more carbon-intensive but also mostly imported from abroad in the EU, with Russia being the primary source of imports in 2021 [7]. Therefore, the increasing demand for fossil fuels in the transport sector also directly contributes to a growing threat to national energy security.

European Commission has committed that in order to decrease energy import dependency and move towards the ambitious climate neutrality goals by 2050, the EU transport sector should reduce its GHG emissions by at least 90 % compared to 1990 levels [8]. Reducing the demand for fossil fuels in the transport system by improving energy efficiency and promoting the rapid switch to alternative fuel vehicles were the main strategies identified by the European Commission [9]. Only a collective approach will lead to the necessary cumulative energy and GHG emission savings to achieve these ambitious targets in less than thirty years, meaning equal contribution and commitment from all European Union member states [10].

Therefore, a more in-depth study on cross-country comparison at the European level is needed to assess which countries have been prosperous in implementing sustainable transport policies and which are off the target in achieving binding climate neutrality goals. It is essential to understand the main characteristics of the transport system in each country and what progress has been made in reducing transport-related GHG emissions.

This study conducted an integrated cross-country comparison of the sustainability level of transport systems in European countries. This paper's main objective was to investigate the main characteristics of the transport system in different European countries and what progress has been made in reducing the total greenhouse gas emissions of the transport system over ten years. To achieve the determined research objective, three main subtasks have been defined: (1) To construct composite transport sustainability index and describe the main characteristics of the transport system for each European country. Based on the results, identify the main similarities and differences between the best and worst-performing countries in terms of transport system sustainability.(2) Conduct a decomposition analysis and examine the key drivers of change in transport-related GHG emissions in European countries over ten years. Identify the progress each country has made in reducing transport-related GHG emissions over the past decade.(3) Identify the policies and strategic directions that have been the main drivers of decarbonization and green transition of transport systems in the best-performing countries.The paper is structured as follows: Section 2 describes the methodological framework applied in the study, Section 3 outlines the main results obtained through the composite transport sustainability index and decomposition analysis, and Section 4 describes the identified policies and strategic directions of decarbonization of the transport system in the countries, Section 5 provides a comprehensive summary and conclusions of the paper.

2. Literature review

Assessing a country's progress on numerous dimensions and factors can be very complex, as many different indicators characterize a country's performance. Moreover, these indicators usually have different units of measurement, making it difficult to obtain a standard view and benchmark that can be used for cross-country comparison. A composite indicator or index could be created to evaluate and compare countries in terms of their sustainability levels. Researchers and analysts prefer the composite index method because it can combine numerous multidimensional sustainability indicators into an integrated measurement. Another advantage of composite indices is that they more accurately reflect the real world by considering the strength of influence of the individual indicators [11]. There are several recent studies in which composite indices were constructed to assess the level of sustainability [11], energy efficiency [12], and productivity [13] in different sectors of the economy. Still, very little research has been conducted to assess the sustainability characteristics of the transportation system across countries in Europe.

A study by Vajjarapu & Verma (2021) constructed a composite adaptability index (CAI) to assess the progress of the urban transport sector in adapting to climate change mitigation strategies. The index included three main pillars such as economic, social, and environmental, which are broken down into three sub-pillars: susceptibility, resilience, and exposure [14]. The authors used the min–max normalization technique to rescale the indicators to standard units of measurement. The Analytic Hierarchy Process (AHP) method was used to determine the weights of the indicators [14]. The results of the AHP were determined using expert judgment. Composite adaptability index scores were determined based on the interlinkages between adaptation, exposure, susceptibility, and resilience of urban transportation. The authors tested three different policy bundles, showing increased adaptive capacity in all scenarios [14].

Gruetzmacher et al. (2021) created a composite indicator (CI) composed of seven sub-indicators of the environmental performance of transport - the share of buses and trains in total passenger transport, the percentage of energy from renewable sources in transport and the allocation of rail and inland waterways in total freight transport, fatalities in transport accidents, greenhouse gas emissions from fuel combustion in transport, average CO_2 emissions per kilometer from new passenger cars, and energy dependence on oil and petroleum products. Data Envelopment Analysis (DEA) and the Benefit of the Doubt model were used to assign weights to the selected indicators. The analysis of the environmental performance of the transport sector was conducted for EU countries for the period from 2015 to 2018. The overall results showed that the EU transport sector improved in 2016 and 2017, and in 2018 it was 4.09 % above the 2015 level [15].

Chen & Silva (2021) applied a four-step approach to construct a transport composite index that measures the smart mobility of English metropolitan areas. First, the authors conducted an in-depth literature review on scientific publications studying smart transport. Second, 49 indicators measuring smart transport systems were selected based on the literature review. Third, three sub-indices of smart transport systems were formed: Accessibility, Sustainability, and Innovation. Then, these sub-indices were combined into the smart transport composite index. The developed method provides a robust framework for assessing smart development in different cities but did not consider the transport system as a whole and excludes rural areas [16].

Although the composite index methodology allows for a comparative assessment of different entities, it lacks to evaluate the progress achieved for each country individually over a more extended time. To address this problem, academic studies often use the decomposition analysis method to assess changes in energy consumption and emissions over time in different sectors of the economy- electricity [17], industry [18], agriculture [19], households [20], and others. Numerous studies used decomposition analysis to measure changes in carbon emissions from the transport sector. For example, a study by [21] used the Logistic Mean Division Index (LMDI) method to examine how transport-related CO_2 emissions in China have changed from 2000 to 2017 and the main factors for the change. The study provided results for both temporal and spatial decomposition analysis. The results of the temporal decomposition analysis showed that changes in income levels significantly affect changes in transport-related CO_2 emissions. In the spatial decomposition, it was found that income and energy intensity, structure, and intensity of the transportation system were the most critical factors for changes in CO_2 emissions from transportation [21].

Another study [22] investigated the main factors influencing changes in CO_2 emissions in Thai road passenger transport using LMDI decomposition analysis. Changes in transport sector emissions were measured based on changes in total population, changes in the country's standard of living, changes in vehicle purchasing power, changes in travel volume demand, changes in specific vehicle energy consumption, changes in the share of certain fuels in total energy consumption, and vehicle emission factors. The result showed that the promotion of biofuel use, which led to a higher share of renewable energy in the total energy mix and a decrease in the total emission factor, was the leading cause of the decreasing emission trend in Thailand's road passenger transport [22].

A study by [23] also used the LMDI technique combined with Tapio's decoupling to examine the progress made in reducing CO_2 emissions from the transport sector in Pakistan during 1984–2018. Changes in transport-related CO_2 emissions were determined based on changes in five primary factors - the CO_2 emission factor, the share of fossil fuels in the total energy balance of transport, energy efficiency, and activity effect. The results showed that the decrease in CO_2 emission factor has contributed the most to reducing CO_2 emissions, while economic growth has caused an increase in CO_2 emissions [23].

The literature review on the use of decomposition analysis to measure transport-related emission changes in European countries is very limited. Only one study was found that applies decomposition analysis to the analysis of transport systems in EU countries. A study by [6] used the Complete Decomposition technique to examine how the CO_2 intensity of the European transport sector has changed over the years and which factors have contributed most to this change. The findings indicated that improvements in energy efficiency in transport, i.e., lower specific energy consumption per average vehicle, contributed most to explaining changes in carbon intensity in the transport sector in EU countries. The study concluded that the EU has failed to reduce GHG emissions in the transport sector and that current efforts were insufficient to contribute to the EU's transition to climate neutrality. Therefore, it is necessary to investigate the factors that influence carbon intensity in the transport sector [6].

3. Methodology

3.1. General framework

The methodological framework of this study was based on three main pillars, as shown in Fig. 1. First, a composite transport sustainability index was constructed for cross-country comparison of the current level of sustainability of transport infrastructure in European countries. The index was built based on 15 different indicators characterizing the transport system, which allows for identifying the main drivers and cornerstones of long-term sustainability. A cross-country comparison of sustainability levels is an effective tool for identifying similarities and differences between different countries and classifying which countries can be considered pioneers in sustainability and which lag behind. The index was further used to set the benchmarks and quickly identify the bottlenecks that national governments should emphasize to accelerate the implementation of more sustainable practices in the transport sector. The composite index method is a comprehensive and effective tool that is often used to make in-depth cross-country comparisons, as its competitive advantage is the integration of an unlimited number of indicators and the complete interpretation of the results, which serves as a helpful tool for decision-making and energy policy development [24].

Second, an LMDI decomposition analysis was conducted to measure the changes in transport-related GHG emissions for each country driven by five main factors: emission intensity effect, RES transition effect, energy intensity effect, economic growth effect, and population growth effect. The results of the LMDI analysis can be used to determine what progress has been made over ten years in reducing GHG emissions in the transport sector.

Finally, an analysis of policy instruments in the transport sector was conducted to examine the measures that countries have implemented to promote the transition to carbon neutrality in transport systems. The policy instruments outlook allowed to identify the differences between the countries with the best and the worst results in transport sustainability.

3.2. Composite index methodology

The methodology of constructing the composite index in this study was based on the calculation procedure described in [25,26,27] which

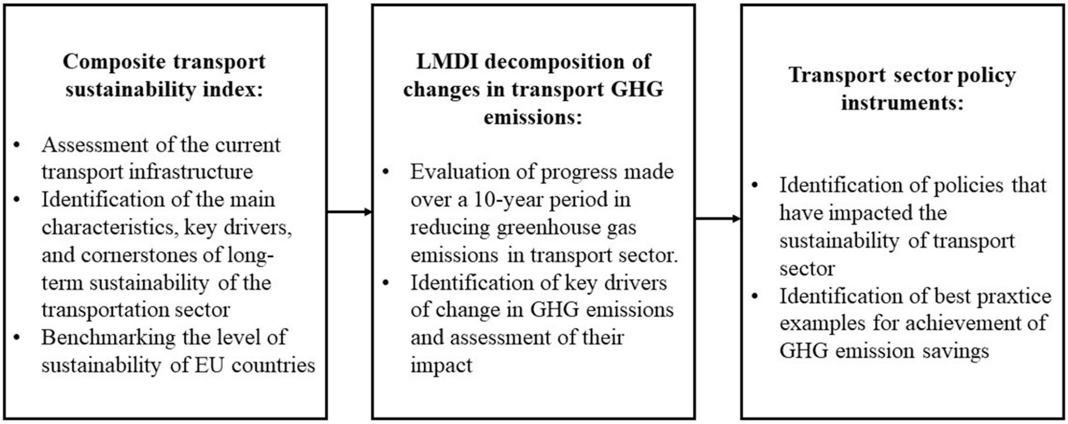

Fig. 1. The methodological framework of the study.

was retrieved from the construction of composite sustainability indices and methodological studies in previous literature. The overall calculation procedure for the construction of the composite sustainability index consisted of the following steps: (1) selection and classification of the indicators, (2) indicator impact evaluation, (3) data normalization, (4) indicator weight assessment, (5) calculation of the sub-indices, and (6) aggregation of the sub-indices into the composite sustainability index. Indicators were selected based on academic research and assessment reports on transport sector sustainability and data availability [24,28]. The selected indicators were classified into four dimensions that characterize the long-term transition of the transport sector to a more sustainable and climate-neutral system. The dimensions were – mobility, sustainability, innovation, and environment. The indicators were selected for all European Union countries (except Malta) and the UK; therefore, the study compared a cross-country transport system sustainability between 27 countries. Data were collected from the Eurostat, European Commission, and Odysee-Mure databases.

Further indicators were assessed according to their impact on overall sustainability, divided into two main groups – positive and negative impact indicators. If an increasing value of the indicator leads to higher sustainability, the indicator was classified as a positive impact indicator. On the other hand, if a growing value for the indicator leads to lower sustainability, the indicator was classified as a negative impact indicator. For example, a higher share of public transport in total land passenger traffic leads to lower energy consumption and greenhouse gas emissions, and thus to greater sustainability. However, if the number of hours spent in road congestion annually increases each year, energy consumption during the journey also increases, negatively impacting sustainability. Table 1 summarizes the selected indicators, classified into representative dimensions and assessed according to their impact on sustainability.

To make the units of measurement of the different indicators comparable, the collected data were further normalized using Eq. (1) – Eq. (2), adopted from [25,26,27].

$$\mathrm{I}_{\mathrm{N}}^{+} = \frac{\mathrm{I}_{\mathrm{act}} - \mathrm{I}_{\mathrm{min}}}{\mathrm{I}_{\mathrm{max}} - \mathrm{I}_{\mathrm{min}}} \tag{1}$$

$$\mathrm{I}_{\mathrm{N}}^{-} = 1 - \frac{\mathrm{I}_{\mathrm{act}} - \mathrm{I}_{\mathrm{min}}}{\mathrm{I}_{\mathrm{max}} - \mathrm{I}_{\mathrm{min}}} \tag{2}$$

where $\mathrm{I}_{\mathrm{N}}^{+}$ is a normalized indicator of positive impact, $\mathrm{I}_{\mathrm{N}}^{-}$ is a normalized indicator of negative impact, $\mathrm{I}_{\mathrm{act}}$ is the actual value of an indicator in a specific country, $\mathrm{I}_{\mathrm{max}}$ is the maximum value of an indicator from all the countries included in the study, $\mathrm{I}_{\mathrm{min}}$ is the minimum value of an indicator from all the countries included in the study.

After normalizing the data, impact weights were assigned for both indicators and dimensions. Following the sustainability framework, which envisages an equal distribution and balance between all dimensions and factors affecting sustainability, this study applied equal weighting to calculate sub-indices and the final composite sustainability index. Previous research has applied various weighting methods (equal weighting, AHP, expert weighting, and others) using the composite index methodology [29], but there is no consensus among researchers on the most appropriate and sound weighting method [30]. While some argue that equal weighting is not the most appropriate choice when analyzing complex problems, others emphasize that equal weighting is more objective than expert judgment or AHP weighting, which can lead to subjective results [31]. The indicators were first aggregated into sub-indices using Eq. (3). After calculating the values of the sub-indices for each dimension, the composite sustainability index was aggregated from all sub-index values using Eq. (4), retrieved from [25,26,27].

$$I_D = \sum w \times I_N^{+} + \sum w \times I_N^{-}, \; w = \frac{1}{n_I} \tag{3}$$

where I_{D} is the sub-index of a specific dimension, w is the weight of an indicator, $\mathrm{I}_{\mathrm{N}}^{+}$ and $\mathrm{I}_{\mathrm{N}}^{-}$ are normalized indicators in each dimension, n_I is

Table 1
Selected indicators, data sources and impact evaluation.

Indicator	Description of the indicator	Impact	Data source
Mobility dimension			
Passenger cars per 1000 inhabitants	A specific indicator that determines the number of passenger cars per 1000 inhabitants in the country	–	[32]
Passenger cars per GDP	A specific indicator measuring the ratio of passenger cars per national GDP	–	[33,34]
Share of public transport in total land passenger traffic	A specific indicator that determines the share of public transport (bus, train, tram, and metro) in the total domestic passenger-kilometers traveled	+	[35]
Annual distance traveled in public transport per capita	A specific indicator measuring the yearly distance traveled per capita in public transport (buses, trains, trams, and metros)	+	[35]
Sustainability dimension			
Quality of roads	The road quality assessment for each country is based on the World Economic Forum survey included in the Global Competitiveness Assessment	+	[36]
Hours spent in road congestion annually	Represent hours spent by the average driver in road congestion each year. The figure accounts for two 30 km trips per day (morning and evening maximum) and 220 working days. It considers all major roads in the Member States for which data are available (approximately 2 500 000 km)	–	[36]
Transposition of EU transport directives	Percentage of EU transport-related directives where the measures taken to improve the transport sector according to EU requirements were notified to the European Commission at the end of the respective year	+	[36]
Consumer satisfaction with urban transport	The assessment is based on the market performance indicator, a composite index that measures the performance according to the consumers' opinions. The data is retrieved from DG JUST Summary of consumer market results.	+	[36]
Innovation dimension			
Market share of electric passenger cars	A percentage of newly registered electric vehicles in the given year, including battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV)	+	[37]
Electric vehicle charging points per 1000 inhabitants	A number of electric vehicle charging points per 100,000 urban residents (persons living in "urban areas" based on DEGURBA classification of urban/rural areas).	+	[37]
Share of alternative fuel vehicles in the total stock of cars	The percentage of alternative fuel vehicles in the total number of vehicles. Include electric vehicles, plug-in hybrid vehicles (PHEVs), and compressed natural gas (CNG) vehicles.	+	[35]
Environmental dimension			
Share of biofuel in transport energy consumption	An indicator measuring the proportion of biofuels in total transport energy balance.	+	[35]
Emissions from the transport sector per number of inhabitants	A specific indicator measuring greenhouse gas emissions in	–	[38,39]

(*continued on next page*)

Table 1 (*continued*)

Indicator	Description of the indicator	Impact	Data source
	relation to the total population of a country.		
Average CO_2 emissions per km from new passenger cars	An indicator measuring the average CO_2 emissions of new passenger cars per kilometer driven.	–	[40]
Share of high emission cars in total sales	An indicator measuring the percentage of total vehicle sales that are high GHG emitting cars (specific emissions per kilometer between 115 and 130 gCO_2/km).	–	[35]

the number of indicators in a dimension.

$$CSI = \sum w \times I_D, \; w = \frac{1}{n_D} \tag{4}$$

where *CSI* is composite sustainability index, w is the value of the weight of a dimension, n_D is the number of dimensions.

3.3. Decomposition analysis methodology

Log-Mean Divisia Index (LMDI) decomposition analysis additive approach was applied to measure changes in aggregate GHG emissions of transport sector determined by: emission intensity effect, RES transition effect, energy intensity effect, economic growth effect, population growth effect. Table 2 summarizes the indicators of LMDI decomposition analysis. The LMDI variables were determined based on the Kaya identity equation. The Kaya identity has been widely used since its introduction in the 1990 s to measure changes in greenhouse gas emissions in different sectors of the economy [19,41]. The original Kaya identity equation was expressed as a multiplication between four main factors that determine changes in greenhouse gas emissions: carbon intensity (CO_2 emissions per energy produced), energy intensity (energy consumed per GDP), economic growth (GDP per population), and population growth (number of inhabitants) [42,43].In this study Kaya identity has been modified and narrowed down to examine the transportation sector in more detail. The result is Eq. (5) [17,19], which reflects all the indicators identified for the analysis of greenhouse gas (GHG) emissions from the transport sector in 28 European countries. A similar approach was used in the studies by [17] and [19], who used the Kaya Identity Equation to determine the factors affecting energy-related CO_2 emissions in the electricity and agricultural sectors using time series data.

$$GHG = \sum_i GHG_i = \sum_i \frac{GHG}{FFC} \cdot \frac{FFC}{TEC} \cdot \frac{TEC}{GDP} \cdot \frac{GDP}{POP} \cdot POP$$
$$= \sum_i EM_i \cdot RES_i \cdot EN_i \cdot GDP_i \cdot POP_i \tag{5}$$

where GHG stands for GHG emissions from fuel combustion in transport, FFC stands for fossil fuel consumption in the transport sector, TEC stands for total energy consumption in the transport sector, GDP stands for gross domestic product, POP stands for the number of inhabitants, *i* denotes specific country. Furthermore, each indicator was expressed as a factor contributing to changes in GHG emissions – *EM* is the emission intensity effect, *RES* is the RES transition effect, *EN* is the energy intensity effect, *GDP* is the economic growth effect, *POP* is the population growth effect.

The changes in GHG emissions from the baseline year (0) to the future year (T) were measured using the additive LMDI approach according to Eq. (6), adapted from [17,19].

$\Delta GHG = GHG^T - GHG^0 = \Delta\ GHG_{em} + \Delta\ GHG_{res} + \Delta\ GHG_{en} + \Delta\ GHG_{gdp} + \Delta\ GHG_{pop}$ (6).

where GHG^T are GHG emissions in the future year, GHG^0 are GHG emissions in the baseline year, and subscripts *em, res, en, gdp, pop* denotes the changes from emission intensity, RES transition, energy intensity, economic growth, population growth effects. Furthermore, changes in each effect were decomposed using Eq. (7)-(11), adapted from [17,19].

Table 2
Description of decomposition analysis indicators.

Factor	Notation	Indicator	Description
Emission intensity effect	*Em*	Total GHG emission in thousand tons of CO_2 equivalents from fuel combustion in transport per total consumption of fossil fuels in the transport sector (GHG_i/FFC_i)	Measures changes in total fossil fuel emissions intensity in the transport sector. Changes in this indicator could indicate changes in modal shift (e.g., higher utilization of public transportation) and transition to less emission-intensive fossil fuels (e.g., shift from diesel oil to LPG, etc.).
RES transition effect	*Res*	Share of fossil fuel consumption in total energy consumption in the transport sector (FFC_i/TEC_i)	Measures the RES transition and the impact of decarbonization on the overall energy mix of the transport sector (reducing the share of fossil fuels and increasing the share of biofuels and electricity in the overall energy balance of the transport sector).
Energy intensity effect	*En*	Total energy consumption of the transport sector per unit of produced gross domestic product (TEC_i/GDP_i)	Measures changes in energy efficiency in the transport sector and shows the energy savings achieved through technical improvements (manufacturing cars with lower specific fuel consumption, more efficient engines, etc.).
Economic growth effect	*Gdp*	Total gross domestic product per capita (GDP_i/POP_i)	Measures changes in economic growth and its impact on higher demand for transportation services (e.g., with higher income, more households can afford to purchase a car, etc.).
Population growth effect	*Pop*	Total population on 1 January (POP_i)	Measures changes in total population. Population growth requires increased energy consumption by the transportation sector due to increased transportation demand.

$$\Delta\ GHG_{em} = \sum_i \frac{GHG^T - GHG^0}{lnGHG^T - lnGHG^0} ln \frac{Em_1^T}{Em_1^0} \tag{7}$$

$$\Delta\ GHG_{res} = \sum_i \frac{GHG^T - GHG^0}{lnGHG^T - lnGHG^0} ln \frac{Res_1^T}{Res_1^0} \tag{8}$$

$$\Delta\ GHG_{en} = \sum_i \frac{GHG^T - GHG^0}{lnGHG^T - lnGHG^0} ln \frac{En_1^T}{En_1^0} \tag{9}$$

$$\Delta\ GHG_{gdp} = \sum_i \frac{GHG^T - GHG^0}{lnGHG^T - lnGHG^0} ln \frac{Gdp_1^T}{Gdp_1^0} \tag{10}$$

$$\Delta\ GHG_{pop} = \sum_i \frac{GHG^T - GHG^0}{lnGHG^T - lnGHG^0} ln \frac{Pop_1^T}{Pop_1^0} \tag{11}$$

In this study, an additive LMDI approach was used because the study's main objective is to measure changes in GHG emissions from transportation in absolute terms. Compared to the multiplicative LMDI approach, which produces a change in the ratio [44], the additive approach allows for a more comprehensive interpretation of the results.

Time series data from 2010 to 2019 were used for all the selected LMDI decomposition analysis indicators of this study. All the data were collected from the Eurostat database. Data on GHG emissions from fuel combustion in transport were compiled from the data set "Greenhouse gas emissions by source sector [env_air_gge]" [45]. Data on fossil fuel and total energy consumption in the transport sector were collected from the data set "Simplified energy balances [nrg_bal_s]"[46], and data on GDP were collected from the data set "GDP and main components [nama_10_gdp]" [47] Data on population were collected from "Population on 1 January [demo_pjan]"[48].

4. Results

4.1. Composite transport sustainability index results: Sustainability level evaluation

The transport composite sustainability index incorporated 15 indicators grouped into four dimensions – mobility, sustainability, innovation, and environment. First, the results for each sub-dimension were analyzed separately. Then, the aggregated index values were examined in detail. The advantage of the composite index methodology is that it allows a comprehensive interpretation of the results. The higher the indicator, sub-index, and aggregated index value achieved, the higher the level of sustainability is in the respective country. The results showed two main benchmarks - the average value and the lowest value. The average value represents the average subindex value of all countries in the respective dimension and was calculated as the arithmetic mean of all values. The lowest value represents the lowest subindex value among the analysed countries, which was determined by a minimum value function in the data set.

Fig. 2 illustrates mobility dimension sub-index values. Mobility dimension indicators describe the socio-economic aspects of transport system sustainability, including two indicators: (1) passenger cars per thousand inhabitants and per GDP, and (2) the share and importance of public transport in total land passenger traffic.

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 in Hungary the use of public transport is more developed and the share of private cars in total passenger transport is lower. High scores were also shown by the Czech Republic and Ireland, which scored high on almost all indicators, as did Hungary. On the other hand, the lowest values of the mobility sub-index were observed in Poland and Lithuania. Although Poland has a relatively high share of public transport in total land passenger transport, the high number of passenger cars per capita and GDP did not allow Poland to achieve higher and more competitive scores in this sub-index category. In turn, the critical aspect for Lithuania is the low public transport intensity, which prevented Lithuania from obtaining a higher score in the mobility sub-index. 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 shows the sub-indices of the sustainability dimension for all the countries studied. This dimension included four sustainability indicators assessed by the European Commission and the World Economic Forum – the quality of roads, the hours spent annually in congestion, the productivity of implementing EU transport directives, and consumer satisfaction with urban transport.

The highest score on the sustainability dimension sub-index was achieved by Estonia, which scored high in all indicators except the quality of roads. Slovakia scored highest in consumer satisfaction with urban transport. Still, low scores for transposition of EU transport directives and quality of roads prevented it from achieving a higher sustainability sub-index score. 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 sub-index. 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. In addition, 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. 4 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 in all

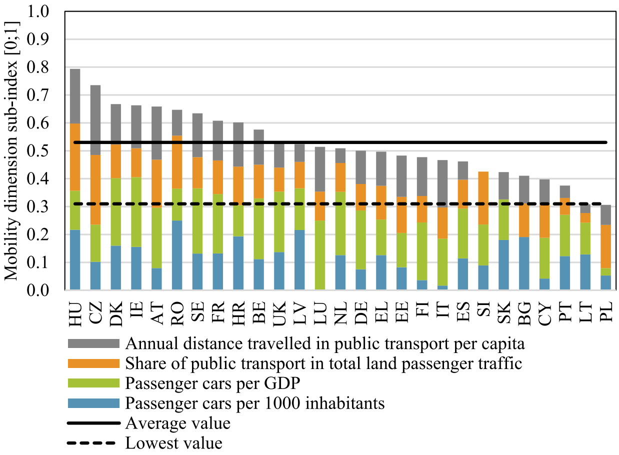

Fig. 2. Mobility dimension sub-index.

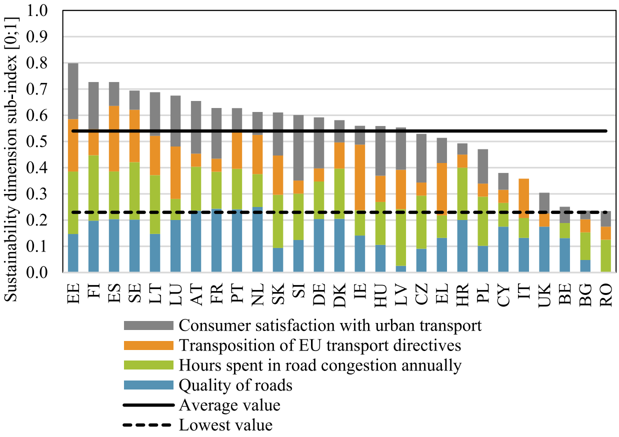

Fig. 3. Sustainability dimension sub-index.

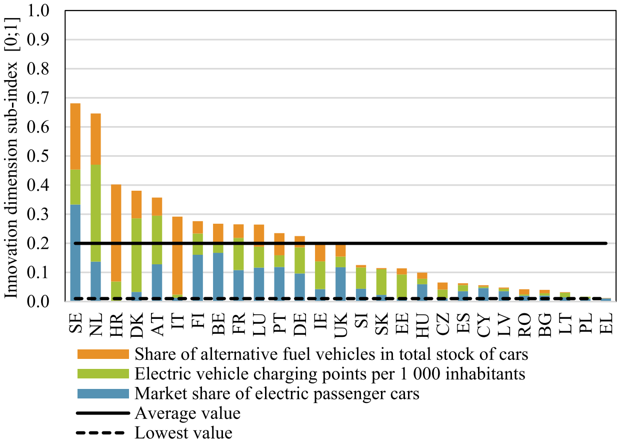

Fig. 4. Innovation dimension sub-index.

indicator positions of the innovation dimension.

Fig. 5 illustrates the sub-indices of the environmental dimension for all countries included in the study. All countries except Sweden hade 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. 6 shows the results of the final transport composite sustainability index. Based on the results, it was possible to identify the most critical aspects for all countries that impact a higher level of sustainability. The innovation and environmental dimensions had the lowest scores compared to the mobility and sustainability dimensions. 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, however, 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. Table 3 summarizes the results of the composite transport sustainability index and sub-indices.

The composite transport sustainability index results were classified into four groups of sustainability levels, as shown in Fig. 6. The first group included countries with a high sustainability level (with a composite sustainability index score equal or above 0.6), such as Sweden (0.67) and the Netherlands (0.61), which have achieved composite transport sustainability index values significantly higher than the average value and who have showed outstanding results compared to other countries. The second group included countries with a moderate level of sustainability, whose composite transport index values ranged between 0.44 (Germany) and 0.55 (Austria) which was equal to or above the average composite index score of all countries analyzed. The third group included countries with a low level of transport sustainability, whose composite transport sustainability index was below the average value of 0.44. The fourth group included countries with very low levels of sustainability (with a composite sustainability index score equal or

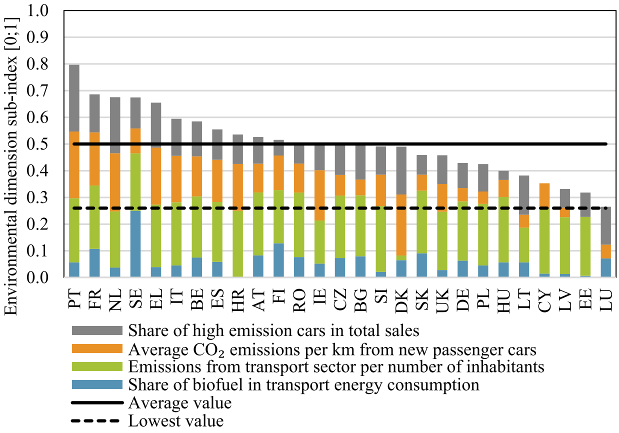

Fig. 5. Environmental dimension sub-index.

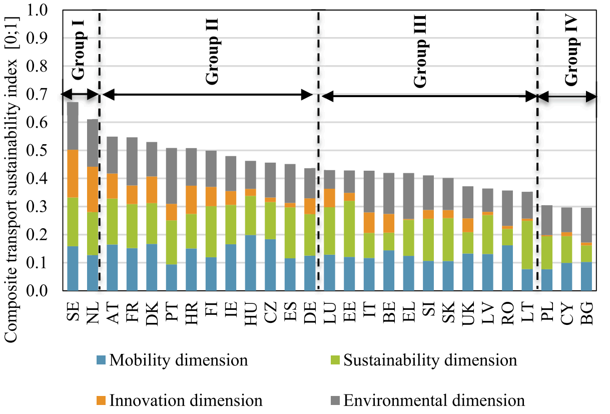

Fig. 6. Composite transport sustainability index.

below to 0.3), with a composite transport sustainability index of 0.3. The fourth group consists of three countries – Poland, Cyprus, and Bulgaria.

4.2. Decomposition analysis results: Progress evaluation

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. The results for each country were reflected in Table 4.

In the EU and UK combined, during the period from 2010 to 2019, GHG emissions of the transport sector increased by 15.3 M tons of CO_2 eq. The main factors for the increase were the economic growth effect (109.7 M tons of CO_2 eq.) and the population growth effect (23.29 M tons of CO_2 eq.). Technological and energy efficiency improvement effect (-102.3 M tons of CO_2 eq.), as well as RES transition effect (-12.6 M tons of CO_2 eq.) and emission intensity effect (-2.7 M tons of CO_2 eq.), were not strong enough to reduce the impact from economic and population growth which pushed the overall GHG emissions in transport to increase.

Fig. 7 shows the aggregate annual results of the LMDI decomposition analysis for the EU and the UK combined. The results showed that transport-related GHG emissions in the EU and the UK combined decreased between 2010 and 2013. The decline is explained by the slowdown in economic growth due to Europe's recovery from the global financial crisis. The decline in economic performance also affected the energy intensity of the transport sector, which fell significantly over the representative period. However, from 2013 until 2019, transport-related GHG emissions in the EU and the UK have increased every year. During the increase period, economic and population growth were the main drivers of this increase. Since 2016, the RES transition effect has been dominant, indicating progress in decarbonizing the transport energy mix by increasing the share of biofuels and electricity in the overall transport energy balance in the EU and UK and other emerging green technologies in transport.

Fig. 8 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 %),

Table 3
Results of composite transport sustainability index and sub-indices.

Country	Mobility dimension sub-index	Sustainability dimension sub-index	Innovation dimension sub-index	Environmental dimension sub-index	Composite transport sustainability index
SE - Sweden	0.16	0.17	0.17	0.17	0.67
NL - Netherlands	0.13	0.15	0.16	0.17	0.61
AT - Austria	0.16	0.16	0.09	0.13	0.55
FR - France	0.15	0.16	0.07	0.17	0.55
DK - Denmark	0.17	0.15	0.10	0.12	0.53
PT - Portugal	0.09	0.16	0.06	0.20	0.51
HR - Croatia	0.15	0.12	0.10	0.13	0.51
FI - Finland	0.12	0.18	0.07	0.13	0.50
IE - Ireland	0.17	0.14	0.05	0.12	0.48
HU - Hungary	0.20	0.14	0.02	0.10	0.46
CZ - Czechia	0.18	0.13	0.02	0.12	0.46
ES - Spain	0.12	0.18	0.02	0.14	0.45
DE - Germany	0.13	0.15	0.06	0.11	0.44
LU - Luxembourg	0.13	0.17	0.07	0.07	0.43
EE - Estonia	0.12	0.20	0.03	0.08	0.43
IT - Italy	0.12	0.09	0.07	0.15	0.43
BE - Belgium	0.14	0.06	0.07	0.15	0.42
EL - Greece	0.12	0.13	0.00	0.16	0.42
SI - Slovenia	0.11	0.15	0.03	0.12	0.41
SK - Slovakia	0.11	0.15	0.03	0.11	0.40
UK - United Kingdom	0.13	0.08	0.05	0.11	0.37
LV - Latvia	0.13	0.14	0.01	0.08	0.36
RO - Romania	0.16	0.06	0.01	0.13	0.36
LT - Lithuania	0.08	0.17	0.01	0.10	0.35
PL - Poland	0.08	0.12	0.00	0.11	0.30
CY - Cyprus	0.10	0.10	0.01	0.09	0.30
BG - Bulgaria	0.10	0.06	0.01	0.12	0.30

Table 4
Decomposition of GHG emissions of transport sector from 2010 to 2019 (thousand tons of CO_2 equivalent).

Country	Δ Emission intensity effect	Δ RES transition effect	Δ Energy intensity effect	Δ Economic growth effect	Δ Population growth effect	Δ GHG emissions in the transport sector	% change from 2010 to 2019
BE - Belgium	−11.9	−399.0	−3764.1	2011.0	1442.0	−721.9	−2.7 %
BG - Bulgaria	243.8	−394.0	334.7	2274.6	−522.7	1936.5	24.1 %
CZ - Czechia	−20.2	−181.5	−1519.6	3643.5	318.3	2240.5	13.3 %
DK - Denmark	747.5	−660.6	−2482.5	1509.0	618.1	−268.6	−2.0 %
DE - Germany	631.0	1442.5	−15809.3	22238.4	2571.7	11074.2	7.2 %
EE - Estonia	−51.2	−63.6	−545.4	793.8	−13.4	120.2	5.3 %
IE - Ireland	282.5	−278.3	−6067.6	5828.6	889.2	654.4	5.7 %
EL - Greece	−78.5	−259.7	−1006.1	−2685.6	−614.3	−4644.2	−20.7 %
ES - Spain	3756.9	−1110.4	−11699.2	7909.3	917.3	−226.2	−0.2 %
FR - France	−5279.8	−2122.7	−11542.6	11119.6	5096.7	−2728.8	−2.0 %
HR - Croatia	48.7	−168.4	−41.3	1137.0	−334.0	642.1	10.8 %
IT - Italy	−1780.9	−294.1	−8829.2	−313.2	1174.0	−10043.4	−8.7 %
CY - Cyprus	−17.0	6.1	−519.9	137.7	154.8	−238.3	−10.0 %
LV - Latvia	23.4	−20.9	−843.0	1197.6	−304.8	52.3	1.6 %
LT - Lithuania	10.4	−13.3	200.2	2283.0	−577.3	1903.0	43.4 %
LU - Luxembourg	−7.2	−265.3	−1420.1	102.9	1235.6	−354.0	−5.4 %
HU - Hungary	53.3	89.8	−412.4	3539.3	−283.7	2986.1	25.5 %
MT - Malta	31.9	−25.7	−140.0	213.9	113.5	193.7	34.7 %
NL - Netherlands	−64.1	−1399.2	−6348.0	2724.1	1328.8	−3758.4	−10.8 %
AT - Austria	−133.7	215.6	−1286.2	1764.7	1362.3	1922.6	8.5 %
PL - Poland	74.1	210.8	−1195.1	17734.0	−59.8	16764.0	34.0 %
PT - Portugal	134.0	27.1	−2524.4	1589.2	−470.1	−1244.3	−6.6 %
RO - Romania	568.9	−536.0	−1003.2	6396.1	−726.9	4698.9	33.0 %
SI - Slovenia	42.5	−164.7	−532.6	894.0	92.7	331.9	6.3 %
SK - Slovakia	113.4	−110.9	−1061.6	1627.4	80.4	648.7	8.7 %
FI - Finland	−138.7	−948.7	−1365.4	646.5	362.1	−1444.2	−11.4 %
SE - Sweden	427.0	−3386.8	−4687.1	1846.8	1639.6	−4160.5	−20.2 %
UK - United Kingdom	−2306.8	−1793.5	−16231.2	11551.8	7713.9	−1065.8	−0.9 %
Total	**−2700.9**	**−12605.4**	**−102342.2**	**109715.0**	**23203.9**	**15270.5**	**1.6 %**

and Bulgaria (24.1 %).

In absolute terms, countries such as Germany, France, Italy, Spain, and Poland accounted for the largest share of changes in transport-related greenhouse gas emissions in the EU. Therefore, even minor changes and improvements in these countries' transport GHG emissions will considerably contribute to the EU's collective GHG emissions

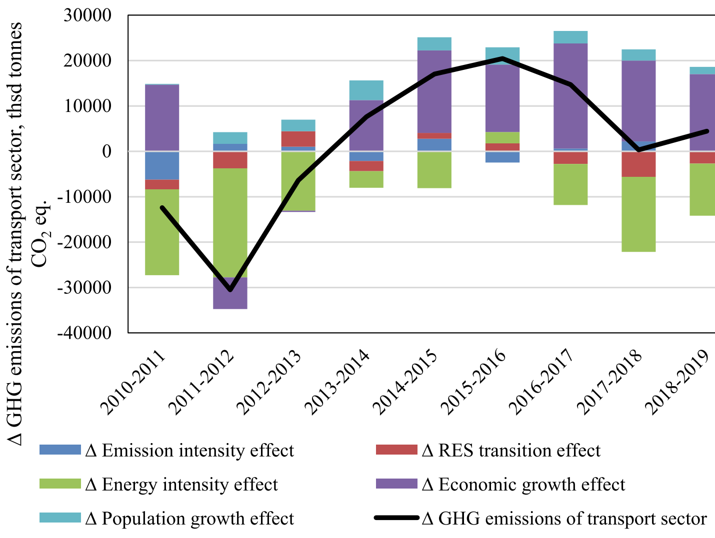

Fig. 7. LMDI decomposition analysis results for EU and UK combined.

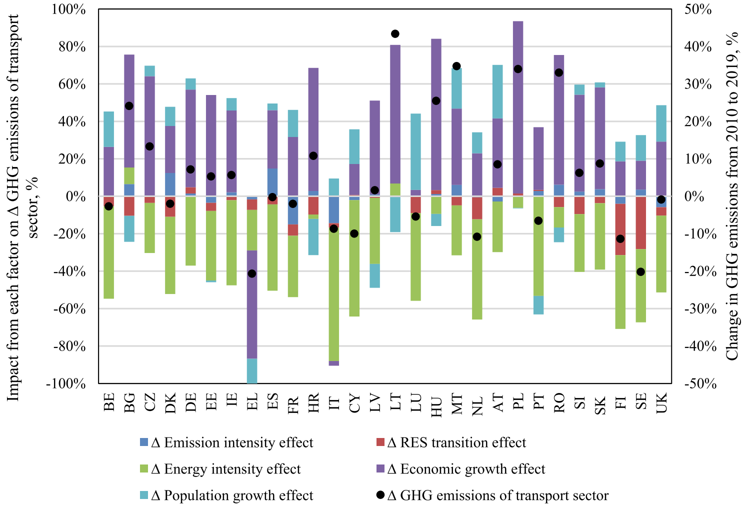

Fig. 8. LMDI decomposition analysis results of GHG emissions of transport sector from 2010 to 2019 (thousand tons of CO$_2$ equivalent) for each country.

reduction target.

LMDI decomposition analysis results showed that in **Belgium** total GHG emissions from transport fuel combustion decreased by 2.7 % from 2010 to 2019. The highest decreases in GHG emissions were observed from 2010 to 2013 and from 2015 to 2017, where energy efficiency improvements played the most crucial role in reducing GHG emissions. Significant improvements in switching from fossil fuels to a higher proportion of alternative fuels were observed from 2015 to 2017, contributing to a substantial reduction in GHG emissions in the representative years. From 2013 to 2019, both economic growth and population growth prevented GHG emissions from the transportation sector from achieving higher reductions. In the composite transport sustainability index, Belgium ranked 17th with a score of 0.42, slightly below the EU average. The results showed that Belgium had the lowest transposition of EU transport directives among EU member states, a high number of hours spent in road congestion annually, and considerably low consumer satisfaction with urban transport, impacting transport sector sustainability. Belgium had a relatively low share of alternative fuel vehicles in the total stock of cars compared to leading countries.

In **Bulgaria**, total GHG emissions from transport fuel combustion increased by 24.1 % from 2010 to 2019. GHG emissions from Bulgaria's transport sector have increased annually since 2013. The only decrease in GHG emissions in the ten years was observed in 2012–2013 due to energy efficiency improvements and the increase in the share of alternative fuels in the representative year. From 2013 to 2015, the energy intensity of the transport sector increased, which means that specific energy consumption of the vehicles increased and no imrovements in energy efficiency were observed. No significant improvements were observed in the transition to renewable energy sources. Moreover, the emission intensity of the Bulgarian transport sector has increased in the period from 2010 to 2019. In the composite transport sustainability index, Belgium ranked 27th with a score of 0.3, the lowest score among the countries. The results indicated that in Bulgaria, the quality of roads, consumer satisfaction with urban transport, and transposition of EU transport directives are deficient, affecting the transport sector's sustainability. In addition, extremely slow progress in innovation was observed in Bulgaria – with low development of infrastructure for alternative fuel cars and promotion of electric vehicles.

In **Czechia**, total GHG emissions from transport fuel combustion increased by 13.3 % from 2010 to 2019. Since 2013, greenhouse gas emissions in the Czech transport sector have increased, with economic growth being the main driver of the increase in emissions. Significant improvements in energy efficiency have been observed from 2016 to 2019, but these were insufficient to offset the economic and population growth that has caused the increase in GHG emissions. Modest improvements in the transition to lower emission intensity fuels and alternative energy were observed over the ten years, with the share of RES in the total energy balance fluctuating significantly over the years. In the composite transport sustainability index, Czechia ranked 11th with a score of 0.46, slightly above the EU average. The Czech Republic ranked high in the use of public transportation. The annual distance traveled by public transport per capita and the share of public transport in total land passenger transport in the country were the second-highest in the EU. However, the inferior quality of roads and transposition of EU transport directives had a negative impact on the sustainability of the transport sector. The main cornerstone of the Czech transport sector was the relatively low progress in developing the market infrastructure for alternative fuels and electric vehicles.

In **Denmark**, total GHG emissions from transport fuel combustion decreased by 2 % from 2010 to 2019. From 2013 to 2018, greenhouse gas emissions in the Danish transport sector have increased annually. Over ten years, two significant decreases in GHG emissions were observed: The first decrease from 2010 to 2013 and the second decrease from 2019 to 2019. The first decrease was caused by a substantial increase in the RES share of the total energy balance and improvements in energy efficiency. The second decrease was entirely due to energy efficiency improvements in the sector. However, over the ten years, the overall fossil fuel emissions intensity of the Danish transport sector has increased, indicating that there has been no progress in modal shift (e.g., increased use of public transport) and increased use of emissions-intensive fossil fuels. In the composite transport sustainability index, Denmark ranked 5th with a score of 0.53. The results show that the Danish transport sector had significantly higher emissions from transport per population than other EU countries. Although there was sufficient infrastructure for electric vehicles and the number of charging points per 1000 inhabitants was one of the highest in the EU, the overall market share of electric cars was low. Relatively low consumer satisfaction with urban transport and the low level of transposition of EU transport directives had a negative impact on the sustainability of the Danish transport sector.

In **Germany**, total GHG emissions from transport fuel combustion increased by 7.2 % from 2010 to 2019. Greenhouse gas emissions from the transportation sector in Germany have increased over ten years, with only two significant decreases. The first decrease was observed in 2011–2012 and the second in 2017–2018. Both declines were due to energy efficiency improvements that resulted in significant energy and emissions savings. Over ten years, a negative trend in the decarbonization of the transportation sector was observed as emissions intensity and fossil fuel share increased. Economic growth and population growth have been the main drivers of the increase in GHG emissions in the German transport sector, and current energy efficiency improvements have not offset the growing energy demand of the transport sector. In the composite transport sustainability index, Germany ranked 13th with a score of 0.44 and was thus at the same level as the EU average. Germany had a high number of passenger cars per 1000 inhabitants and a lower share of public transport in total land passenger transport, which affected the achievement of more significant GHG emission reductions in the transport sector. Germany had a relatively low share of alternative fuel vehicles in the total stock, a relatively high share of high emission vehicles in commercial sales, and higher average CO_2 emissions per km for new passenger cars, which affected the sustainability of the transport sector.

In **Estonia**, total GHG emissions from transport fuel combustion increased by 5.3 % from 2010 to 2019. Over the ten years, GHG emissions from the transport sector in Estonia have increased annually, with only two decreases observed. The first decrease in GHG emissions was achieved in 2012–2013 due to energy efficiency improvements and the reduction in total population. The second decrease was observed in 2018–2019. It was achieved through a combination of energy efficiency measures, transitioning to less emissions-intensive modes of transportation and fuels, and promoting the use of RES in vehicles. The economic growth factor was the leading cause of the increase in GHG emissions in the Estonian transport sector, which could not be offset by energy efficiency improvements and the transition to RES by 2017. In the composite transport sustainability index, Estonia ranked 15th with a score of 0.43, slightly below the EU average. The relatively high number of passenger cars per capita increased the pressure on energy demand in the Estonian transport sector. Lack of development of transport infrastructure for alternative fuels and extremely low share of biofuels in transport energy consumption compared to other EU countries and high average CO_2 emissions per km for new passenger cars affeced the achievement of more considerable GHG emission reductions. Estonia had a competitive advantage in sustainability indicators, such as good transposition of EU transport directives, high consumer satisfaction with urban transport, and fewer hours spent in road congestion annually.

In **Ireland**, total GHG emissions from transport fuel combustion increased by 5.7 % from 2010 to 2019. Greenhouse gas emissions from the Irish transport sector have increased slightly over the past ten years. Although significant energy efficiency improvements have been made in the Irish transport sector since 2014, they have not been sufficient to offset economic growth, which has increased overall GHG emissions. Overall emissions intensity has grown over the ten years, indicating that there has been no positive change toward modal shift (greater use of public transportation) and conversion to less emissions-intensive fuels. In the composite transport sustainability index, Ireland ranked 9th with a score of 0.48, which was above average value. The results showed that in Ireland, consumer satisfaction with urban transport was low, and the number of hours spent annually in congestion was high, which had a negative impact on the sustainability of the transport sector. The low market share of electric cars and the low share of biofuels in transport energy consumption, as well as the relatively high share of cars with high emissions in total sales compared to other EU countries, prevented the Irish transport sector from achieving higher GHG emission reductions.

In **Greece**, total GHG emissions from transport fuel combustion decreased by 20.7 % from 2010 to 2019. The economic crisis hit the Greek economy hard and had a significant impact on energy demand and greenhouse gas emissions from the transport sector, which decreased significantly from 2010 to 2012. However, from 2013 to 2019, GHG emissions from the Greek transport sector have increased every year except for 2016–2017. Since 2013, no progress has been observed in improving energy efficiency and shifting to RES in the Greek transport sector. In the composite transport sustainability index, Greece ranked 18 h with a score of 0.42, which was slightly below the EU average value. There has been no significant progress in the development of alternative fuel vehicle infrastructure, as Greece ranked among the last in the market share of electric cars and charging stations per capita, as well as in the share of alternative fuel vehicles in the total stock and the share of biofuels in transport energy consumption. Low consumer satisfaction with urban transport and the high number of hours spent in road congestion annually also had a negative impact on the sustainability of the transport sector in Greece.

In **Spain**, total GHG emissions from transport fuel combustion decreased by 0.2 % from 2010 to 2019. The Spanish transport sector experienced a significant decrease in GHG emissions from 2010 to 2012, primarily due to lower economic growth, which reduced energy demand and emissions. However, since 2012, GHG emissions from the Spanish transport sector have increased annually. A slight improvement has been observed in increasing the share of renewable energy sources in the total energy balance of the Spanish transport sector. In the composite transport sustainability index, Spain ranked 12 h with a score of 0.45, which was slightly above the EU average value. The results showed that the insufficient infrastructure for alternative fuel vehicles compared to other EU countries (low market share of electric cars and a low number of charging stations per capita, as well as low share of alternative fuel vehicles in the total vehicle stock and low share of biofuels in total transport energy consumption) prevented the Spanish transport sector from reducing GHG emissions faster. In addition, the relatively low share of public transport in passenger transport and low consumer satisfaction with urban transport had a negative impact on the sustainability of the Spanish transport sector. However, a competitive advantage of the Spanish transport sector was the relatively high quality of roads, the good transposition of EU transport directives, and the lower number of hours spent in road congestion annually.

In **France**, total GHG emissions from transport fuel combustion decreased by 2 % from 2010 to 2019. Greenhouse gas emissions from the transport sector in France have fluctuated over the past ten years but have been significantly reduced. The reduction in greenhouse gas emissions has been achieved mainly by improving energy efficiency. However, significant improvements have also been achieved by increasing the share of RES in the overall energy balance of transport and reducing the overall emissions intensity, indicating a positive modal shift towards greater use of public transport and a switch to less emission-intensive fuels. In the composite transport sustainability index, France ranked 4th with a score of 0.55, significantly above the EU average value. France's competitive advantage was its relatively low average CO_2 emissions per km for new passenger cars, which contributed significantly to achieving savings through energy efficiency improvements and placed France among the countries with low transport emissions per population. In addition, France was above average in developing sufficient infrastructure for alternative fuel vehicles - it performed competitively in the share of electric cars in total transport and has a higher average share of biofuels in transport energy consumption. The main cornerstone of the French transport sector was the relatively low transposition of EU transport directives.

In **Croatia**, total GHG emissions from transport fuel combustion increased by 10.8 % from 2010 to 2019. GHG emissions from the transport sector in Croatia have experienced significant fluctuations over the last ten years. GHG emissions have increased significantly, but reductions have been achieved in three periods: 2010–2012, 2013–2014, and 2017–2018. Increasing the share of RES in total transportation energy consumption did the most to reduce GHG emissions. However, these improvements were insufficient to offset increasing energy demand due to increasing economic activity that pushed GHG emissions to increase. In the composite transport sustainability index, Croatia ranked 7th with a score of 0.51, significantly above the EU average value. The competitive advantage of the Croatian transport sector lied in the high share of alternative fuel vehicles in the total fleet, the high quality of roads, and fewer hours spent in traffic jams each year, which contributed to the sustainability of the transport sector. However, although Croatia has made progress in developing infrastructure for electric vehicles, it had the lowest value for the share of biofuels in transport energy consumption. In addition, low implementation of EU transport directives and low consumer satisfaction with urban transport had a negative impact on the development of a competitive and sustainable transport sector in Croatia.

In **Italy**, total GHG emissions from transport fuel combustion decreased by 8.7 % from 2010 to 2019. Greenhouse gas emissions from the transport sector fluctuated in Italy, but overall showed a downward trend and have decreased significantly over ten years. Improvements in energy efficiency contributed most to reducing GHG emissions. Still, reductions in emissions intensity and a higher share of RES also played an essential role in the Italian transport sector. The results indicated that greater promotion of the use of RES in the transport sector has been achieved, and a modal shift has taken place, meaning that public transport has been used more during this period. In the composite transport sustainability index, Italy ranks 16th with a score of 0.43, which was slightly below the EU average value. Overall, the Italian transport sector was characterized by a high number of passenger cars per capita, making it challenging to achieve GHG emission reductions. Consumer satisfaction with urban transport was lowest in Italy, and the implementation of EU transport directives was insufficient, which affected the long-term sustainability of the transport sector. Italy was among the countries with a relatively high share of alternative fuel vehicles in the total vehicle fleet and progress in developing electric vehicle infrastructure compared to other EU countries. Still, it had a low share of biofuels in transport energy consumption. Italy had a competitive advantage with low average CO_2 emissions per km for new passenger cars and a relatively low share of high emission vehicles in total sales, contributing to a more significant reduction in greenhouse gas emissions.

In **Cyprus**, total GHG emissions from transport fuel combustion decreased by 10 % from 2010 to 2019. In Cyprus, GHG emissions from the transport sector significantly reduced in the first half of the ten years, while an increasing trend was observed in the second half of the period. However, overall, a significant reduction in GHG emissions from the transport sector was achieved due to the decreases from 2010 to 2014. Changes in economic growth were the main factor influencing the decline and increase in GHG emissions. Over the period, improvements in energy efficiency and reductions in overall emissions intensity were achieved. In the composite transport sustainability index, Cyprus ranked 27th with a score of 0.30, which was significantly below the EU average value. The transport sector in Cyprus was characterized by a high number of passenger cars per capita and the highest share of high emission cars in total sales, which significantly impacts greenhouse gas emissions. In addition, sustainability was negatively affected by the low implementation of EU transport directives, low consumer satisfaction with urban transport, and high annual traffic congestion. Cyprus had experienced insufficient infrastructure development for alternative fuel vehicles and a low share of biofuels in transport energy consumption.

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 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 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.

In **Lithuania**, total GHG emissions from transport fuel combustion increased by 43.4 % from 2010 to 2019, the most significant increase among EU countries. Economic growth and the rise in energy intensity of the transport sector have caused GHG emissions in the Lithuanian transport sector to skyrocket. There have not been sufficient improvements in energy efficiency; on the contrary, the Lithuanian transport fleet has become more inefficient on average by increasing its specific consumption (l/100 km). The decrease in population was the only factor that caused greenhouse gas emissions from the transport sector to decrease consistently but could not compensate for the high increase. There were initially minor positive trends in two periods towards an increasing share of RES in the Lithuanian transport sector: first in 2011–2012 and then in 2016–2017. In the composite transport sustainability index, Lithuania ranked 24th with a score of 0.35, which is significantly below the EU average value. The Lithuanian transport sector had a meager share of public transport in total land passenger transport and high average CO_2 emissions per km for new passenger cars compared to other EU countries, which prevented achieving energy and emission savings in the sector. In addition, Lithuania had a prolonged development of infrastructure for alternative fuel vehicles and a low share of biofuels in transport energy consumption. However, the low number of hours spent in road congestion annually and the relatively high level of consumer satisfaction with urban transport positively impaced the Lithuanian transport sector.

In **Luxembourg**, total GHG emissions from transport fuel combustion decreased by 5.4 % from 2010 to 2019. Luxembourg has succeeded in reducing its GHG emissions from the transport sector over ten years, with energy efficiency improvements contributing most to the substantial reductions. There have also been positive trends to increase the share of RES in the transport sector. The growing population was the leading cause of the increase in GHG emissions. Still, energy efficiency improvements were significant enough to offset this growth and achieve an overall reduction in GHG emissions from the transport sector in Luxembourg. In the composite transport sustainability index, Luxembourg ranked 14th with a score of 0.43, which was slightly below the EU average value. Luxembourg had the highest number of passenger cars per capita and is thus the country with the highest emissions from the transport sector per number of inhabitants. It also performed poorly in terms of average CO_2 emissions per km from new passenger cars, which had implications for achieving greater GHG emission reductions. In contrast, Luxembourg had a high quality of roads, high transposition of EU transport directives, and high consumer satisfaction with urban transport, which positively impacted the sustainability of the transport sector. Luxembourg had also made relatively good progress compared to other EU countries in developing sufficient infrastructure for alternative fuel vehicles.

In **Hungary**, total GHG emissions from transport fuel combustion increased by 25.5 % from 2010 to 2019. Since 2013, the Hungarian transport sector has experienced a gradual and significant increase in greenhouse gas emissions. The effect of economic growth and lack of improvements in energy efficiency and adaptation to renewable energy were the main factors that caused this. In general, the energy intensity of the Hungarian transport sector has increased since 2013, showing a trend towards the use of more inefficient vehicles. No progress has been observed in increasing the share of RES in transport. In ten years, the percentage of RES has decreased in the Hungarian transport sector, and the emission intensity has increased. In the composite transport sustainability index, Hungary ranked 10th with a score of 0.46, which was above the EU average value. Hungary stood out by having one of the highest shares of public transport in total land passenger traffic. The poor quality of roads and low transposition of EU transport directives had a negative impact on the sustainability of the Hungarian transport sector. Hungary had progressed in developing the electric vehicle market, but development was still below the EU average. The low share of biofuels in transport energy consumption, the high share of high-polluting vehicles in total sales, and the high average CO_2 emissions per km for new passenger cars prevened significant GHG emission savings from being achieved in the Hungarian transport sector.

In **Malta**, total GHG emissions from transport fuel combustion increased by 34.7 % from 2010 to 2019. In Malta, a sharp increase in GHG emissions from the transport sector was observed over ten years, mainly due to economic and population growth. While improvements in energy efficiency and shift to renewable energy sources were observed, these were not sufficient to offset the impact of economic and population growth, resulting in an overall increase in GHG emissions. Overall emission intensity has increased in Malta's transport sector, showing a negative trend in using less public transport or the choice of more emission-intensive fuels. Due to lack of data, Malta was not included in the composite index, so no results from the composite index could be explained for Malta.

In the **Netherlands**, total GHG emissions from transport fuel combustion decreased by 10.8 % from 2010 to 2019. The Netherlands has experienced a significant decrease in GHG emissions from the transport sector over ten years. However, this reduction was mainly achieved in the first half of the decade, while progress in reduction decreased in the second half of the decade. Improvements in energy efficiency and RES in the transport sector played an important role in reducing GHG emissions in the Netherlands. A slight decrease in emissions intensity indicated a positive trend toward greater use of public transportation or a switch to lower-emission fuels. In the composite transport sustainability index, the Netherlands ranked 2nd with a score of 0.61. Compared to other EU countries, the Netherlands was a leader in developing sufficient infrastructure for alternative fuel vehicles and building an adequate number of electric vehicle charging stations per capita. However, the Netherlands lagged in increasing the share of biofuels in transport energy consumption. Another cornerstone of the sustainability of the Dutch transport sector was the relatively low level of consumer satisfaction with urban transport.

In **Austria**, total GHG emissions from transport fuel combustion increased by 8.5 % from 2010 to 2019. Economic and population growth were the main reasons for this increase. Improvements in energy efficiency in the Austrian transport sector have been observed, but no improvements have been made in increasing the share of RES in transport. The percentage of fossil fuels in the total energy balance of the transport sector in Austria has increased, leading to an increase in greenhouse gas emissions. In the composite transport sustainability index, Austria ranked 3rd with a score of 0.55. The main cornerstones of the Austrian transport sector were the high number of passenger cars per capita and the low implementation of EU transport directives, which affected the level of sustainability in transport. Austria had developed sufficient infrastructure for alternative fuel vehicles above the EU average.

In **Poland**, total GHG emissions from transport fuel combustion increased by 34 % from 2010 to 2019. The Polish transport sector has experienced significant increases in greenhouse gas emissions over ten years, with the highest annual increases in the decade's second half. While improvements in energy efficiency were observed during this period, these improvements were not significant enough to offset the increasing economic growth that drove the overall increase in GHG emissions. Throughout the ten years, the Polish transport sector increased its share of fossil fuels in the total transport energy balance, which also increased the emissions intensity of the transport sector. However, 2017 was the first year in which a positive transition to an increasing RES in transport was observed. In the composite transport sustainability index, Poland ranked 25th with a score of 0.3, significantly below the EU average value. The Polish transport sector was characterized by a high number of passenger cars per capita and per GDP, which put additional pressure on transport sector incentives to reduce GHG emissions. In addition, EU transport directives were poorly implemented, and average CO_2 emissions per km for new passenger cars were high. Poland had one of the worst developed alternative fuel vehicle infrastructures in the EU and a low share of biofuels in transport energy consumption, which was a crucial cornerstone for developing a sustainable transport sector in Poland.

In **Portugal**, total GHG emissions from transport fuel combustion decreased by 6.6 % from 2010 to 2019. Over ten years, Portugal succeeded in reducing greenhouse gas emissions from the transport sector. However, this was only achieved through significant reductions in the first half of the decade (2010–2013), as GHG emissions from the transport sector in Portugal have increased since 2013. Energy efficiency improvements and population decline were the main reasons for the decrease while increasing economic growth was the main reason for the increase in GHG emissions. In general, no significant improvement was observed in increasing the share of RES in Portugal's transport sector. In the composite transport sustainability index, Portugal ranked 6th with a score of 0.51, which was significantly above the EU average value. The main cornerstones of the transport sector in Portugal were the low share of public transport in total land passenger traffic and the low level of consumer satisfaction with urban transport. Portugal had made progress in developing infrastructure for alternative fuel vehicles, but the share of biofuels in total transport energy consumption was relatively low. Portugal had a competitive position in having a low share of high emission cars in total sales and low average CO_2 emissions per km from new passenger cars.

In **Romania**, total GHG emissions from transport fuel combustion increased by 33 % from 2010 to 2019. Romania was one of the countries that experienced a sharp increase in greenhouse gas emissions in the transport sector over ten years. The increasing economic growth mainly caused this increase. Over ten years, improvements were observed in energy efficiency and in increasing the share of RES in the total energy balance of the transport sector. However, these improvements did not offset the impact of economic growth, which led to an increase in total GHG emissions in the Romanian transport sector. Emission intensity has increased, suggesting that there has been a shift towards less use of public transport and higher use of high emission fossil fuels. In the composite transport sustainability index, Romania ranked 23th with a score of 0.36, significantly below the EU average value. Romania had the worst road quality among EU countries, low consumer satisfaction with urban transport, and low transposition of EU transport directives, which negatively affected the long-term sustainability of the transport sector. Poor and far below the average progress was observed in developing sufficient infrastructure for alternative fuel vehicles. The relatively high share of high-polluting vehicles in total sales and the low share of biofuels in transport energy consumption put additional pressure on Romanian efforts to reduce greenhouse gas emissions in the transport sector.

In **Slovenia**, total GHG emissions from transport fuel combustion increased by 6.3 % from 2010 to 2019. Over ten years, Slovenia has increased its greenhouse gas emissions from the transport sector. However, significant reductions were achieved in 2012–2013 and 2018–2019. Significant improvements in energy efficiency and increasing the share of RES in transport were achieved. Increased activities to expand renewable energy in transport were observed from 2016. In the composite transport sustainability index, Slovenia ranked 19th with a score of 0.41, which was slightly below the EU average value. The insufficient transposition of EU transport directives had a negative impact on the long-term sustainability of the transport sector in Slovenia. The most important cornerstone for Slovenia was the slow progress in developing sufficient infrastructure for alternative fuel vehicles, which was far below the EU average, and the meager share of biofuels in transport energy consumption.

In **Slovakia**, total GHG emissions from transport fuel combustion increased by 8.7 % from 2010 to 2019. Over ten years, greenhouse gas emissions from fuel combustion in the transport sector in Slovakia have increased. However, from 2010 to 2014, GHG emissions decreased, and from 2015 to 2019, a gradual increase began. Significant improvements in energy efficiency were observed only in the first half of the decade, while the energy intensity of the Slovak transport sector increased significantly from 2015. This indicated that in the last five years, an increase in specific fuel consumption for cars in Slovakia was observed, which increased GHG emissions. However, since 2015, the emission intensity has decreased significantly in the transport sector of Slovakia. In the composite transport sustainability index, Slovakia ranked 20th with a score of 0.40, which was slightly below the EU average value. The transport sector in Slovakia was characterized by a low share of public transport and poor quality of roads, which had a negative impact on the sustainability of the transport sector. Relatively little progress has been made in developing sufficient infrastructure for alternative fuel vehicles, which prevented a reduction in greenhouse gas emissions. In addition, the high share of high emission vehicles in total sales and the high average CO_2 emissions per km for new passenger cars are other cornerstones that put pressure on Slovak intentions to reduce GHG emissions in the transport sector.

In **Finland**, total GHG emissions from transport fuel combustion decreased by 11.4 % from 2010 to 2019. In the last ten years, Finland has achieved significant reductions in greenhouse gas emissions in the transport sector. Energy efficiency and increasing the share of RES in transport have played the primary role in reducing greenhouse gas emissions. The most substantial impact of increasing the percentage of RES on reducing GHG emissions was achieved in 2013–2014. The overall emissions intensity of the transportation sector in Finish has decreased over ten years, indicating increased use of public transportation and a decrease in the use of emissions-intensive fossil fuels. In the composite transport sustainability index, Finland ranked 8th with a score of 0.50 above the EU average value. The high number of passenger cars per 1000 inhabitants and the high share of high emission cars in total sales were the main cornerstones for the sustainability of the Finnish transport sector. Finland had a competitive advantage due to the good quality of roads, consumer satisfaction with urban transport, and the low number of hours spent in traffic jams each year. Good and above-average progress in developing market infrastructure for electric vehicles and a higher share of biofuels in the transport sector compared to other EU countries enabled Finland to reduce greenhouse gas emissions more.

In **Sweden**, total GHG emissions from transport fuel combustion decreased by 20.2 % from 2010 to 2019, which was the most significant decrease among EU countries. From 2010 to 2018, Sweden showed stable annual reductions in fossil energy share and an increase in RES and electricity share in the total energy balance of the transport sector (except for the year 2019). Since 2010 stable annual energy efficiency improvements and shift to transportation with lower specific fuel consumption. From 2018 to 2019 significant decrease in fossil fuel emission intensity was achieved with suggested that there has been a significant modal shifts (increases in public transportation usage) and/or a switch to utilization of lower emission intensity fossil fuels. Despite stable economic and population growth, Sweden achieved a 20.2 % reduction in transport sector GHG emissions from 2010 to 2019. In the composite transport sustainability index, Sweden ranked 1st with a score of 0.67. Sweden had one of the most developed market infrastructures for alternative fuels compared to other EU countries, both in terms of the share of electric vehicles and the share of biofuels in the energy consumption of the transport sector and in the total stock of motor vehicles, which allowed for a greater reduction of greenhouse gas emissions in the transport sector. The relatively low consumer satisfaction with urban transport, the higher average CO_2 emissions per km for new passenger cars, and the higher share of high emission cars in total sales compared to other countries were the main cornerstones for the sustainability of the Swedish transport sector.

In the **UK**, total GHG emissions from transport fuel combustion decreased by 0.9 % from 2010 to 2019. Over ten years, the UK has achieved modest declines in GHG emissions from the transport sector. Significant decreases in GHG emissions were observed in 2010–2013 and 2016–2019, while an increase between these two periods (2013–2016). Economic growth and population growth were the main drivers pushing GHG emissions to increase in the UK. However, improvements in energy efficiency, increases in RES, and reductions in emissions intensity were the main factors leading to a decrease in GHG emissions over the representative periods. In the composite transport sustainability index, the UK ranked 21st with a score of 0.37 below the EU average value. According to the results, the UK showed modest progress in developing sufficient infrastructure for alternative fuel vehicles. The main cornerstones for the sustainability of the transport sector in the UK were the high number of hours spent on the road congestion annually and the low share of biofuels in transport energy consumption, which prevented a higher reduction of greenhouse gas emissions in the transport sector.

4.3. Combined results of the composite sustainability index and decomposition analysis

The results showed substantial differences in the average composite sustainability index scores achieved between the Eastern, Western, and Nordic countries, which was also reflected in the GHG emission reductions achieved over a 10-year period from 2010 to 2019. Table 5 summarizes the main results of the composite sustainability index and decomposition analysis by grouping the results into two main country groups – Nordic European countries, Western European countries, Eastern European countries.

The summary results showed interlinkages and consistency in the obtained results of the two main methods of this study - composite sustainability index and decomposition analysis. Namely, country groups with higher average composite sustainability index scores, such as the Nordic and Western European countries, have also achieved the highest reductions in CO_2 emissions in the transport sector. In contrast, the Eastern European country group, which indicated the lowest average composite sustainability index score, hasn't achieved a reduction in CO_2 emissions in the transport sector, but showed a significant increase.

The Nordic countries outperformed other countries by on average indicating significantly higher scores in all dimensions of transport sustainability with the highest dominance in innovation and sustainability dimension indicators. While the Eastern European countries have, on average, reached almost the same level as the Western European countries in the indicators of mobility and the sustainability dimension, they still lagged significantly behind in the indicators of the environmental and innovation dimension.

5. Discussion

5.1. Differences between Nordic, Western, and Eastern European countries

Due to the different national renewable energy targets, development strategies, political incentives and priorities set in the transport sector in the individual European countries, different development trends in the transport sector can be observed from country to country. Although the Renewable Energy Directive introduced in 2009 set the same target for all EU member states, namely, to achieve a 10 % share of renewable energy in total energy consumption in the transport sector by 2020, countries have achieved very different results by 2020 [49]. Of the 27 EU Member States, only 12 countries met this target, with Sweden (31 %) and Finland (13.4 %) reporting the highest levels, followed by the Netherlands (12.6 %), Luxembourg (12.6 %), Estonia (12.2 %), Hungary (11.6 %), Belgium (11 %), Slovenia (10.9 %), Italy (10.7 %), Malta (10.6 %), Austria (10.3 %) and Ireland (10.2 %). Majority out of which nine are Eastern European countries indicated RES share in transport below 10 % by 2020, with the lowest results in Greece (5.3 %), Lithuania (5.5 %), Poland (6.6 %), Croatia (6.6 %) and Latvia (6.7 %) [49].The part of these deviations in achieved RES targets by EU-27 countries can be explained by the degree of strictness of national RES targets in each country and the interest, intentions, and support of national governments in setting more ambitious decarbonization targets for the transport sector. In general, the majority of EU countries have not been strict to take strong action to mitigate climate change from activities in the transport sector, which is reflected in the results of the study, where the majority of countries have increased their transport-related CO_2 emissions and have not met the binding renewable energy target.

Sweden, which is the absolute leader in the EU in the share of RES in transport and which have achieved the largest reductions in transport-related CO_2 emissions over the study period, has set ambitious RES targets for transport sector and has used various policy mechanisms to incentivize the transition to low-carbon fuels, such as setting a carbon tax on fuels, which has been in place since 1991 (to limit fossil fuel consumption), and introducing tax exemptions for sustainable biofuels (to encourage the development of alternative fuel infrastructure) [49].

The results of this study showed that innovation dimension is the main cornerstone that differentiates Eastern and Western European countries from Nordic countries which lead in electric and alternative fuel vehicle market and infrastructure. The results are consistent with the study by Robaina & Neves (2021), which examined the differences in CO_2 emission intensities achieved by the transport sector between 2008 and 2018. The study found significant differences between Nordic (Denmark), Western (Germany, Spain, France, Italy, Portugal), and Eastern (Lithuania, Slovenia) European countries. Of the 8 countries studied, Denmark stood out as having the largest decrease in fossil fuel consumption relative to electricity consumption in the transport sector. Complete decomposition of CO_2 emissions intensity results for the transport sector for Denmark showed that since 2009, the country has gradually increased its share of electricity consumption by decreasing the share of fossil fuel consumption in total energy consumption in the transport sector. As a result, in a ten-year period Denmark has reduced its transport CO_2 emission intensity to decrease. However, in most Western European countries, measures to electrify the existing fleet have only been observed since 2012–2013 and have fluctuated significantly since then. In the Eastern European countries, this trend can only be

Table 5

Summary results of the composite sustainability index and decomposition analysis.

	Mobility dimension sub-index	Sustainability dimension sub-index	Innovation dimension sub-index	Environmental dimension sub-index	Composite transport sustainability index	% change from 2010 to 2019
Nordic European countries (SE, FI, DK)	0.15	0.17	0.11	0.14	0.57	−12.6 %
Western European countries (NL, FR, PT, ES, DE, LU, IT, BE, EL, UK, AT, IE)	0.13	0.14	0.06	0.14	0.47	−1.5 %
Eastern European countries (HU, CZ, SK, RO, PL, BG, EE, LV, LT, HR, SI, CY)	0.13	0.13	0.02	0.11	0.39	19.7 %

observed from 2015 onwards [6].

In the Nordic countries, institutional support and policy incentives to promote the development of energy efficient and low-carbon transport systems have been in place since the 1990 s. Sweden, for example, introduced an energy and carbon tax on transportation fuels in 1995, Finland developed and implemented an environmental driving education program in driving schools in 1994, and Denmark introduced an environmental fee for vehicle owners in 1999, charging annual fees based on average fuel consumption. However, in most Eastern and Western European countries, carbon neutrality in the transport sector has received greater attention only since the 2010 s [50]. Therefore, strong institutional support and policy incentives are needed for the development of a sustainable and carbon–neutral national transportation infrastructure.

Institutional support, however, will only be effective if combined with policy mechanisms and instruments aimed at improving general knowledge and awareness of environmental issues in society. Environmental awareness and sense of public responsibility is directly linked with one's decision making which also include the choice of daily transportation habits. Without awareness, acceptance and adaptation to new conditions, no improvement can be achieved. Awareness of and attitudes toward climate challenges and the transport sector's impact on them vary from country to country, with significant differences observed between Nordic, Western and Eastern European countries. According to the recent European Commission's Eurobarometer survey [51], environmental awareness and public responsibility for environmental issues were greater in Nordic and Western European countries, and therefore people in these countries participate more in activities that could reduce the impact of climate change, including transport habits. For example, when asked whether people regularly use environmentally friendly alternatives (walking, cycling, public transport or car sharing) to their private car, Eastern European countries such as Poland with 14 %, Hungary with 16 % and Romania with 17 % had the lowest values among all EU-27 countries. By contrast, the Netherlands, Germany and Sweden had the highest figures, at 56 %, 51 % and 42 % respectively. Similar results were also observed in a question asking whether people take into account the carbon footprint of their transport when planning long-distance travel and choose less carbon-intensive modes of transport. Here, Eastern European countries such as Bulgaria (2 %) and Latvia (2 %) reported the lowest values, while Sweden (27 %) and the Netherlands (26 %) reported the highest [51].

Another research highlighted substantial differences in environmental awareness differences between Nordic, Western and Eastern European countries. A study by Khanam et al. (2022) evaluated European expert's conjoined level of willingness to reduce the carbon footprint of main consumption groups such as food, waste, energy, and transport. The study found that out of the analyzed consumption groups transport showed the worst results, indicating that there is limited and low willingness to change the current transport habits (reducing the usage of private car, switching to higher use of public transport, preferring walking and cycling) in order to reduce the carbon emissions [52]. The study highlighted that people who use public transportation instead of their own cars have both economic benefits and contribute to significant emissions savings. It was estimated that using public transportation saves about $9738 and nearly 2177.24 tons of carbon dioxide annually (for a round trip of about 32.2 km). More importantly, people who walk and bike not only reduce fuel consumption and emissions, but also reduce traffic congestion and noise pollution [52].

Yet despite these benefits, people are still reluctant to change their current transportation habits [52], which are mostly driven by higher levels of convenience, travel time comfort and other factors [53]. It was also argued in a study by Safronova et al. (2022), which conducted a study to investigate people's transportation behavior and their willingness to switch from private to public transportation. The results showed that only 4 % of the respondents would be willing to switch to public transport if the price of private car transport increased significantly. The authors argued that in addition to the economic and technical factors that influence this, there are still prejudices and stereotypes against public transport [53,54]. Therefore, for transport policies to be effective, greater attention should be devoted to changing current perceptions and attitudes towards public transport, as economic incentives such as increasing fuel prices and making public transport more affordable alone will not be able to have a significant effect on modal shift [53,55].

The results of this study showed that, on average, Eastern European countries performed significantly worse than Nordic and Western European countries in the indicators of the environmental dimension. The poor environmental performance of Eastern European countries was also reflected in the energy efficiency indicators monitored by Odysee Mure, which showed similar results for CO_2 intensity of transport (kCO_2/EUR2010) and specific fuel consumption (l/100 km) indicators. The data showed that the CO_2 intensity of transport in Eastern European countries is almost three times higher than in Nordic countries and twice higher than in Western European countries. A similar trend was observed in the vehicle efficiency indicator, where Latvia had the highest average specific fuel consumption of 9.41 l/100 km and Luxembourg had the lowest average specific fuel consumption of 5.5 l/100 km from the available data [56].

The lower energy efficiency and higher carbon intensity of the transport sector in Eastern European countries could be due to the significantly older average stock of cars in Eastern European countries compared to Western European countries. Eurostat 2020 data [33] showed that several EU countries have a high share of old passenger cars in the total stock, with the highest share of passenger cars over 20 years old in Poland (40 %) and Estonia (32.7 %). In contrast, the share of passenger cars with an age of only two years or less was reported to be highest in Luxembourg (22.0 %) and France (16.7 %) [33]. Eastern European countries are usually a secondary car sales market, where used cars are mostly exported from Western European countries [57]. Therefore, the average vehicle stock in Eastern European countries is older and less efficient. The lower average income level of Eastern European countries is one of the reasons why secondary car sales market is more prevalent in Eastern Europe.

5.2. Policy measures to promote low-carbon transport infrastructure development

Assessing the impact of policies is a significant challenge, especially in the transport sector, where decarbonization is based on technical solutions (e.g., converting the fleet from fossil fuels to electricity) and changing habits. The method described in the paper and its application for the analysis and comparison of EU countries was an attempt to highlight those instruments of sustainable transport policy that have yielded the best results so far. We highlighted several essential policy measures (directions) for transport decarbonization from the analysis. They were described below, together with an in-depth analysis of these policies in the best-performing countries. Various data sources have been used to analyze policy measures, including IEA and Odysee Muree transport policy databases, national energy and climate plans, and country-specific policy planning documents.

5.2.1. Facilitate the transition from private cars to public transport

The role of public transport in the composite transport sustainability index was primarily reflected in three indicators: annual distance traveled in public transport per capita, the share of public transport in total land passenger traffic, and consumer satisfaction with urban transport.

The Czech Republic and Hungary obtained the highest scores for two of the three indicators – Share of public transport in total land passenger traffic and Annual distance traveled in public transport per capita (0.25 and 0.25 for the Czech Republic and 0.24 and 0.2 for Hungary, respectively). Austria also had a high score in the second indicator (0.19). Meanwhile, Slovenia and Estonia scored the best for the indicator Consumer satisfaction with urban transport (0.25 and 0.21, respectively). The Czech Republic, Germany, France, Luxembourg, Hungary, and Finland performed equally well in the user satisfaction indicator and closely followed the two leaders (0.19).

Several common trends characterize leading countries. Firstly, there is the emphasis on rail transport as the backbone of the transport system. The measures aim to continuously improve the railway infrastructure and connect it to other modes of transport. The Czech Republic, Hungary, and Austria also use the metro, significantly increasing the number of kilometers traveled by public transport in densely populated areas.

Secondly, there is a strong link between national and municipal strategic planning levels. Municipalities are closest to their citizens. Strategic municipal mobility plans ensure the promotion of the use of public transport following the conditions of the particular place. For example, in the Czech Republic, there is a requirement that Strategic Sustainable Urban Mobility Plans (SUMPs) should be developed and regularly updated in cities with a population of over 40,000 [58]. Also, Austria has a well-established urban transport planning framework that incorporates SUMPs [59]. though their implementation is voluntary. The Austrian example also demonstrates cooperation between the national and municipal planning levels through the national ‘klimaaktiv mobil’ climate protection program, which offers cities and municipalities consultation and financial support to implement mobility management measures [60]. The role of municipalities and cities is critical to ensure a gradual transition to modern zero-emission or alternative-fuel vehicles and to implement measures to promote public transport. One of the essential indicators is consumer satisfaction with public transport. Slovenia and Estonia showed the highest score on this indicator in the composite transport sustainability index (0.25 and 0.21, respectively). Satisfaction with the public transport service is usually determined by indicators such as the availability and accessibility of public transport, frequency and connectivity, travel time and safety, information, comfort, and price [61]. Slovenia, which had one of the highest shares of public transport in total land passenger transport in Europe, has made the improvement of public transport infrastructure one of the key strategic priorities of Slovenia’s national energy and climate plan. Adjusting timetables, integrating urban transport and establishing a public passenger transport operator were among the specific measures aimed at making the use of public transport more attractive to consumers [62]. Financial incentives in the form of subsidized tickets areused to increase the competitiveness of public transport [63].

Estonia is an interesting example since it have investigated the free public transport introduced in Tallinn for locals. Results showed that the share of public transport use stopped declining for a couple of years [56]. However, the free public transport policy did not reach its goal of reducing car journeys (still, most commuting is done by car) [64]. At the same time, this was not an optimal indicator, as the attitude of the existing public transport users towards service and quality could be seen. Continuous improvements in public transport would deter existing users from leaving and increase their positive evaluation. However, it is just as important (if not more important) to attract new public transport users who previously used private cars. Several studies on modal shift from private cars to public transport suggest that optimal policy instruments should strike a balance between pull (i.e. “carrot” and push (i.e. “stick”) policies [65,66,67]i.e., public transport improvements and the burden on car users. Previous research shows that the motivation to choose public transport over the car was low [68,69]. Further research and evaluation would be desired on soft policies, especially for mode shift (information campaigns, test drives, etc.).

5.2.2. *Promotion of electric mobility and infrastructure*

In the scope of this study, the dimension of electric mobility promotion and infrastructure was characterized by two indicators: market share of electric passenger cars and electric vehicle charging points per 1000 inhabitants.

Sweden had the highest score for the market share of electric passenger cars (0.33), followed by Belgium, Finland, the Netherlands, and Austria. However, the score for these countries was significantly lower (0.13–0.17). It should be noted that the value of this indicator for several countries was 0 or very close to it (Croatia, Estonia, Poland, Greece, Czech Republic, Italy, Lithuania). It means that the progress in these countries in electric mobility infrastructure development was significantly lower than in leading countries. The highest score for the electric vehicle charging points per 100 thousand people was in the Netherlands (0.33), Denmark (0.25), Austria (0.17), Sweden (0.12), and France (0.11). Similarly, for the indicator of the market share of electric passenger cars, the value was 0 or very close in several countries (Greece, Cyprus, Romania, Poland, Bulgaria, Latvia, Italy). The results of the composite sustainability index were consistent with the results of the LMDI decomposition analysis, which showed that the most significant transition to zero-emission vehicles over a ten-year period was observed in Sweden, Finland, the Netherlands.

The Netherlands, Belgium, Sweden, and several other countries have seen a sharp increase in electric cars since 2018, driven by well-designed and implemented policies. The Netherlands has the highest number of electric cars per capita in the European Union. The Netherlands also has the most developed charging infrastructure. There are about 150 charging stations per 100 km^2 of the country’s territory. In comparison, Germany, which ranked second for the number of electric cars per capita, had only 12 charging stations per 100 km^2.

The rapid development of electric vehicles can be observed in countries with long-term energy policies that indicates the importance of electric vehicles for decarbonizing the transport sector and prioritize electric mobility. For example, in the Netherlands, the country’s long-term goal is to make all new cars CO_2-free by 2030. The focus for achieving this ambitious goal is on electrical mobility.

In countries where the development of electric mobility was already well advanced, a balanced spectrum of policy instruments, both penalty (i.e. “stick”) and reward (i.e.“carrot”) measures can be observed. The main reward and pull measure (i.e.“carrot”) is financial support to purchase an electric vehicle. Support for installing charging stations for different target groups, including businesses and individuals, is also provided in several countries, including the Netherlands and Belgium. Registration and operating tax exemption are widely used in countries with a high number of electric vehicles. Companies’ tax incentives are another successful instrument used in the Netherlands, Germany, and Sweden.

The penalty and push (i.e. “stick”) instruments focus mainly on introducing a higher tax burden on CO_2-emitting vehicles to motivate users to choose electric vehicles. In Denmark, Belgium, Finland, and many other countries, the vehicle registration tax is dependent on CO_2 emissions. Another instrument that targets the use of internal combustion engines and the transition to electric vehicles is the introduction of so-called green zones in cities, where only low-carbon or zero-emission vehicles are allowed to enter.

Most EU countries use similar instruments to promote electrical mobility. The main differences are the number of instruments and their monetary value (e.g., the amount of reimbursement granted). In countries with significant progress in the development of electric mobility, instruments can be observed that target not only individual end-users but also larger groups such as municipalities or associations. In all these countries (with advanced electric mobility), support for infrastructure development and research funding in electrical mobility is a mandatory requirement. In Sweden, for example, the value of fringe benefits for company cars is ensured to encourage the purchase of low-emission vehicles at the corporate level and thus achieve a higher penetration of environmentally friendly vehicles [70].

5.2.3. *Promotion of other alternative fuels*

In the context of the study, the dimension of the promotion of other alternative fuels was characterized by two indicators: the share of alternative fuel vehicles in the total passenger car fleet and the share of biofuels in energy consumption in transport.

Sweden had the highest value for the indicator measuring the share of biofuels in energy consumption in transport (0.25), followed by Finland, France, and Slovakia, but with significantly lower values (0.09–0.13). The value of this indicator was 0 or very close to it for several countries such as Croatia, Estonia, Latvia, and Cyprus. The highest values for the indicator measuring the share of alternative fuel vehicles in the total vehicle stock were found in Croatia (0.33), Italy (0.27), Sweden (0.23), and the Netherlands (0.18). In the remaining countries, this value was significantly lower. For several countries, the value of this indicator was 0 or very close to it (Lithuania, Greece, Poland, Latvia, Slovakia, etc.), which means that these countries were significantly behind in the transition to alternative fuels compared to the leaders.

Sweden and Finland are among the countries with the highest biofuel blends of around 21 %. This is the main reason for the high share of biofuels in total final energy consumption in the transport sector. Finland and the Netherlands also have relatively high biofuel blending requirements (20 % and 17 %, respectively). Another successful instrument used in several countries with high biofuel use (e.g., Sweden) is the introduction of specific CO_2 tax systems for fuels. The principle is to increase taxes on fossil fuels and decrease taxes on biofuels. The lower the CO_2 content of biofuels, the greater the tax benefits. The application of such a mechanism helps increase the economic attractiveness of biofuels. In Sweden, for example, pure biodiesel is also actively used without fossil fuels (about 5 % of total energy consumption in transport).

Countries with a high share of biofuels in their overall transport energy balance also have in common that they actively use biofuels and promote the production of biofuels in the country through a variety of instruments. The focus is on producing advanced biofuels, although the technologies used differ in some cases. For example, Sweden relies on thermochemical processes to produce biodiesel, while Finland is among the world leaders in producing bioethanol using hydroprocessing technology. Such an approach is sustainable as it brings economic and social benefits to the country and reduces CO_2 emissions by reducing the use of fossil fuels. At the same time, several countries, especially the Scandinavian countries, restrict the use of agricultural products to produce first-generation biofuels through various instruments.

Several countries are actively promoting the use of biomethane in transportation. Sweden is a leader, with biomethane accounting for about 1.5 % of the country's total energy consumption. To promote biomethane, a combination of policy instruments is typically used. First, subsidies for biogas or biomethane production (Germany, Denmark, Finland, Italy). Second, non-taxation of biomethane (Sweden and Finland) or other tax incentives for both biomethane producers and users (Germany, Sweden, Netherlands, and Italy). Third, granting different feed-in tariffs for the transmission of biomethane (Germany, Denmark, Finland, Italy, and the Netherlands). As well as an additional mechanical blending of biomethane to fossil fuels and subsidies for infrastructure development.

Many countries that are actively using biomethane in transport are also supporting the use of compressed natural gas (CNG) in transport through various policy instruments. The main instruments for CNG promotion are subsidies for end-user infrastructure and reduced taxes, and the government sometimes also supports the purchase of CNG-fueled vehicles (Italy, the Netherlands, Austria, Croatia).

Many countries actively using biomethane in transport also support the use of compressed natural gas (CNG) in vehicles through various policy instruments. The main instruments for CNG promotion are subsidies for end-user infrastructure and reduced taxes. Governments sometimes also support the purchase of CNG-fueled vehicles (Italy, the Netherlands, Austria, and Croatia).

For both biomethane and CNG use in transport, the most significant progress has been made in countries that actively promote the use of these fuels in public transport and trucks (e.g., by limiting CO_2 emissions through public procurement) in addition to the instruments mentioned above.

The promotion of hydrogen has been identified as one of the priorities in the long-term strategies of several countries. However, only a few countries are currently using policy instruments. The Netherlands is a clear leader in the use of hydrogen. The main instruments currently used to promote hydrogen are infrastructure, production, and research.

5.2.4. *Promotion of energy efficiency and achievement of energy savings*

In the context of the study, the energy efficiency dimension was characterized by five indicators: passenger cars per 1000 inhabitants, passenger cars per GDP, transport sector emissions per number of inhabitants, average CO₂ emissions per km of new passenger cars, the share of high-polluting emission cars in total sales.

From an energy efficiency perspective, it is crucial to ensure that the number of cars per capita is as low as possible but to increase the use of public transportation and encourage bicycles and public transportation. The passenger car per 1000 inhabitants indicator measures the concentration of passenger cars in the country's total passenger transport. It showed that Luxembourg (0.0), Italy (0.02), and Finland (0.04) are among the countries with a high concentration of passenger cars, while Romania (0.25), Hungary (0.22), and Latvia (0.22) had the lowest. However, it is essential to consider whether the low number of cars is not due to the low-income level of the population and the inability to buy a private car. This was accounted for in the indicator measuring passenger cars per GDP, which showed that Belgium (0.0) and Poland (0.03) had a high concentration of cars in relation to the country's total GDP. In contrast, Luxembourg and Ireland (0.25), Sweden (0.24), and the Netherlands (0.23) had the lowest values and therefore are less concentrated with passenger cars in total traffic.

Another essential aspect of energy efficiency in the transport sector is the promotion of low-emission vehicles in the total sales of new passenger cars to prevent the new purchase of high emission vehicles. The results showed that Estonia (0.00), Latvia (0.14), Lithuania (0.19), and Poland (0.19) had the lowest efficiency, having the highest average CO_2 emissions per km for new passenger cars. In addition, Cyprus (0.00), Hungary (0.14), and Latvia (0.28) were among the countries with the highest share of highly polluting vehicles in total sales. These results indicated that vehicles with larger engines are more preferred than energy efficiency benefits obtained by smaller and more efficient vehicles in these countries. This suggests that these countries did not have stringent policies that would limit the purchase of new high emission vehicles. In contrast, the best performing countries in promoting energy efficiency were Portugal (0.25), Denmark (0.23), and the Netherlands (0.22). These countries had the lowest values for average CO₂ emissions per km of new passenger cars. Similarly, Portugal (0.25), the Netherlands (0.21), and Denmark (0.18) hd the lowest proportion of highly polluting vehicles as a proportion of total sales. The results of the LMDI decomposition analysis showed that the Netherlands, Belgium, Denmark, Italy, Sweden, Finland, France and Portugal experienced significant energy efficiency improvements over a ten-year period, which were the main reason for the decline in transport related GHG emissions in these countries.

It is usually challenging to reduce the number of cars in economically developed countries, so penalty (i.e. "stick") policy instruments are preferred. For example, the introduction of so-called green zones in cities, where only zero- or low-emission vehicles are allowed to enter (Germany, Netherlands, Belgium). Another solution is to introduce a system of high taxes on vehicle CO_2 emissions. For example, Sweden has introduced specific taxation depending on the CO_2 emissions of the vehicle, while Finland, the Netherlands and Portugal impose a specific tax on the purchase of passenger cars [62]. Mandatory standards are also used to control the level of specific emission intensities allowed for new vehicles. For example, Germany sets CO_2 emission standards for passenger cars and vans, as well as a passenger car label for fuel consumption. The effectiveness of this type of restrictive instruments is shown not only in reducing the number of passenger cars but also in reducing CO_2 emissions, both in terms of population and number of vehicles. Reward (i.e. "carrot") policy instruments are also used in many countries to facilitate the transition from inefficient, low-emission vehicles to financial vehicles, such as financial support for purchasing new zero-emission vehicles and the phasing out of old, carbon-intensive vehicles. In France, for example, Bonus-malus scheme for the purchase of new vehicles (bonus-malus écologique) was developed to support consumers by subsidising the scrapping of old vehicles and subsidising clean and efficient vehicles [62].

Close cooperation between national and local authorities is essential to achieve results and promote energy efficiency in the transport sector to encourage the implementation of harmonized policy instruments that complement each other without creating competition, rising vehicle prices and related infrastructure, and overall fragmentation of the sector.

6. Conclusions and recommendations

This study used a three-level assessment of transport sector sustainability across European countries. First, this study assessed the overall sustainability level of the transport sector in all European Union Member States and the United Kingdom using the composite sustainability index method for cross-country comparison. The composite sustainability index for the transport sector included 15 different indicators divided into four main dimensions – mobility, sustainability, innovation, and environment. The results showed a high potential to increase the sustainability of transport in all countries included in the study since none of the countries were close to the maximum score of 1. Sweden and the Netherlands can be considered benchmarks for higher long-term sustainability, with scores of 0.67 and 0.61, respectively. Most countries lagged in innovating transportation systems by providing the necessary infrastructure for electric vehicles and alternative fuel cars. The results showed that more emphasis should be placed on increasing the use of public transport and reducing the number of passenger cars per 1000 inhabitants. In the sustainability dimension, the lowest results were in terms of the productivity of implementing EU transport directives and the level of consumer satisfaction with public transport. In the environmental dimension, the high proportion of high-polluting vehicles and the average CO_2 emissions per km from new passenger cars were the main cornerstones for greater energy and emissions savings in the transport sector.

The proposed composite sustainability index is a static assessment of the transport system at a given time (the year 2017). To see the dynamics of progress, the sustainability index has been supplemented with a second research step. LMDI decomposition analysis was conducted to evaluate each country's progress in moving the transport sector toward carbon neutrality over ten years. The decomposition analysis measured the changes in transport-related GHG emissions for each country, driven by five main factors: emission intensity effect, RES transition effect, energy intensity effect, economic growth effect, and population growth effect. The results showed that technological, energy efficiency and renewable energy transition effects have not been sufficient to reduce economic and population growth impacts, which continuously pushed greenhouse gas emissions in transport to increase. Although the majority of European countries have failed to reduce transportation-related greenhouse gas emissions over a ten-year period, some countries have performed significantly better than others, with Greece (-20.7 %), Sweden (-20.2 %), Finland (-11.4 %), and the Netherlands (-10.8 %) achieving the most significant emissions reductions over the ten years from 2010 to 2019.

The combined results of the composite sustainability index and decomposition analysis revealed significant differences between Nordic, Western, and Eastern European countries. The results of this study showed that the level and deployment of innovations in transport is the main cornerstone that differentiates the Eastern and Western European countries from the Nordic countries, which are leaders in the electric vehicle and alternative fuel vehicle market and infrastructure. Persistent development of renewable energy infrastructure in transport has helped the Nordic countries achieve the highest CO_2 emission reductions in the transport sector compared to other European countries. Eastern European countries indicated the lowest results in all main dimensions of transport sustainability. The poor performance of Eastern European countries was mainly due to the inefficient and carbon-intensive vehicle fleet, unsatisfactory public transport, lack of innovation, and slow transition to low-carbon alternatives. Finally, the concluding section provided an in-depth overview of some of the policies pursued by certain countries in the transport sector, which have allowed them to take precedence over other countries. The considered sustainable development directions of the transport sector include facilitating the transition from private cars to public transport, promotion of electric mobility and infrastructure, promotion of other alternative fuels, and energy efficiency measures. The overall assessment was that the leading countries constitute a comprehensive approach, including a wide variety of policy measures, including a strong emphasis on energy-saving activities and the transition to zero-emission transportation. Specific targets in national energy and climate plans, as well as collaboration and involvement of all stakeholders and end-users, were key features of the sustainability policies of top-performing countries such as Sweden, the Netherlands, and Finland. In contrast, 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 general, the results suggested that there might be different approaches to developing effective sustainability policies in the Nordic, Western, and Eastern European countries. 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. Countries should focus on raising environmental awareness of the impact of transportation on climate change, because the public's sense of responsibility determines the decision on the most appropriate mode of transportation. For maximum impact, all countries should balance pull mechanisms (i.e., rewards) and push mechanisms (i.e., sanctions) in developing sustainable transportation policies.

7. Limitations and suggestions for further research

Combining the composite index and decomposition analysis can provide valuable insights into transport sector characteristics and comparison across countries. However, some limitations should be considered when evaluating the research results. First, the study results rely on the quality and reliability of the data. The selection of indicators for the composite transport sustainability index is closely linked to the data availability. For the reason of unavailability of reliable and comparable data, some important transportation system-related indicators may be excluded from the analysis, e.g., cycling and pedestrian infrastructure development. The omission of such indicators could potentially alter the overall results of the index. Further research should assess the impact of such potential new indicators. There are other indicators that could be incorporated into the development of a composite sustainability index to allow for more in-depth analysis of country comparisons in sustainable transport. For example, indicators that measure (1) the level of environmental awareness, knowledge, public acceptance, and attitudes; (2) the level of institutional support and public funding allocated to sustainable transport; (3) research and development in emerging technologies such as hydrogen systems in transport; (4) the level of urbanization and regional transport infrastructure; (5) the level of energy independence and reliance on fuel exports.

The composite transport sustainability index of this study included several qualitative assessment indicators retrieved from the EU Transport Scoreboard developed by the European Commission, such as consumer satisfaction with urban transport, transposition of EU directives, and the quality of roads. Since data sources on these indicators are secondary and there is little information about the respective surveys from which the data are derived, the composite transport sustainability index results may be potentially biased. Besides, the composite transport sustainability index uses data from 2017, as this was the most recent data available. Data on the selected indicators should be updated in future research to see progress. Assessing the impact of the COVID-19 pandemic could be of particular interest.

Data validity is one of the most important cornerstones in studies using composite indices and decomposition analyzes. The results obtained are very sensitive to the data inputs used in the construction of the indices. It is important to emphasize that countries have different procedures and attitudes towards the necessary data monitoring, e.g., one country may have strict control over the recording of correct data, while in another country there is no strict control over it. Therefore, in further research, a coefficient that evaluates the reliability of the data could be introduced and applied and used in the calculation of the indices.

Moreover, expert judgment or AHP weighting could be used instead of equal weighting to account for the different impacts of each indicator on the sustainability of the overall transportation system. Similarly, the LMDI decomposition analysis results suggest that future research on LMDI in the transport sector needs to evaluate options for constructing a decomposition with more specific indicators and for different transport modes. A more detailed construction of decomposition equations would allow for a more in-depth assessment of the transport systems across Europe.

Policy analysis revealed numerous challenges in identifying and evaluating policies in different countries. It is not always possible to make a qualitative comparison of policy measures, as the available information sources lack detail, for example, the yearly amount of funding to support ETL purchase. I.e., policies in countries have different "weights" in terms of impact and scale, and qualitative evaluation (whether or not a policy is mentioned in the planning documents) may not reflect the effectiveness of the policy. In addition, there are many policy measures whose impact cannot be assessed in isolation from the standard policy. This applies particularly to actions that encourage a modal shift from private cars to public transport (e.g., building a modality point or installing public transport timetables, etc.). Further research should focus on a more detailed policy instrument assessment, including quantitative policy performance and investment indicator comparison.

CRediT authorship contribution statement

Kristiāna Dolge: Formal analysis, Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Investigation, Data curation, Visualization. **Aiga Barisa:** Formal analysis, Conceptualization, Writing – original draft, Validation, Supervision. **Vladimirs Kirsanovs:** Formal analysis, Conceptualization, Writing – original draft, Validation, Supervision. **Dagnija Blumberga:** Formal analysis, Conceptualization, Validation, Supervision.

Declaration of Competing Interest

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

Data availability

Data used in this study were collected from publicly available databases - Eurostat, Odysee Mure, European Commision.

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PAPER 4: FROM TARGETS TO ACTION: ANALYZING THE VIABILITY OF REPOWEREU IN ACHIEVING ENERGY SUSTAINABILITY

From Targets to Action: Analyzing the Viability of REPowerEU in Achieving Energy Sustainability

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Abstract. EU's energy sector is facing turbulent times as it strives to strengthen energy independence without losing sight of providing affordable and sustainable energy to all. The European Commission's REPowerEU plan to accelerate the EU's energy transition places additional pressure on each member state's path to energy sustainability. To reach this objective, policymakers must assess the present energy sustainability levels of each member state, identify areas for development, and monitor the county's progress over time. The purpose of this article is to analyze and compare the energy sustainability levels of the EU member states using a variety of indicators and to identify key cornerstones for advancing their energy transition. This study develops an energy sustainability composite index (ESCI) in order to unravel 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. Log-Mean Divisia Index (LMDI) decomposition analysis is utilized to track the progress of energy policy in achieving reductions in energy-related CO_2 emissions from 2015 to 2019. Changes in CO2 emissions were decomposed using Kaya identity factors to determine which of the following factors contributed the most to the changes: changes in emission intensity, energy intensity, economic or population growth. The results indicate that all EU member states have untapped potential for improving energy sustainability.

1 Introduction

Growing global concerns about energy security and climate change 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 [1]. To strengthen energy self-sufficiency while achieving a sustainable green energy transition, the European Commission launched REPowerEU Plan in 2022: Joint European action for more affordable, secure and sustainable energy [2]. The REPowerEU plan is intended to address all aspects of the energy trilemma that determines national energy systems in order to ensure that sufficient efforts are placed on decreasing fossil energy import dependence from Russia while delivering energy at an affordable price to end-consumers. This can be accomplished by taking a more active role in implementing sufficient energy efficiency measures and deploying a higher proportion of renewable energy resources [3].

Effective energy policy should incorporate an optimal trade-off between economic affordability and environmental sustainability; however, the current energy crisis caused mainly by the Russian war in Ukraine has increased the importance of enhancing energy independence rapidly, which may place additional pressure on the current green energy transition targets [4]. Even though the European Commission is responsible for establishing the overall strategy and vision for the European Union, national climate policies, their effectiveness, and the priorities of national governments have a significant impact on the efforts of each member state to increase energy sustainability [5].

To assess the EU's ability to meet the European Commission's ambitious REPowerEU targets, it is necessary to examine the progress made so far and the ranking of EU member states in relation to these interconnected goals in energy sustainability. The purpose of this study is to determine each EU member state's current level of energy sustainability and how it has historically contributed to the EU's transition towards a sustainable, affordable, and secure energy system. The development of a comprehensive and effective energy policy relies heavily on the use of reliable data and rigorous evaluation methods [6]. To this end, this research employs a combination of two data-based mathematical approaches to provide a comprehensive assessment of the sustainability of the European Union's energy policies. The findings of this study have the potential to significantly inform the development of more robust energy policies.

The structure of the paper is as follows: Section 2 describes the integrated assessment approach utilized in this study, Section 3 describes the attained results from composite index and LMDI decomposition analysis, and Section 4 provides the study's primary conclusion.

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2 Methodology

In this study, an integrated assessment approach combining both composite index and decomposition analysis methods is used. The combination of both methods makes it possible to examine the current state of energy sustainability in individual EU countries as well as to assess progress in the transition to green energy, thus providing a comprehensive analysis and unlocking multiple aspects of energy sustainability. Using both methods allow to identify the key factors affecting national energy sustainability and the drivers of change in the green transition. At first composite index is calculated to evaluate the existing situation in energy sustainability levels, then decomposition analysis is applied to measure and monitor progress in energy policy of each EU's member state.

2.1. Composite index

The composite index method is used to construct energy sustainability composite index (ESCI). The main advantage of this method is that it allows combining numerous different indicators with different units of measurement to obtain a single metric - the composite index [7]. In addition, the results are easy to interpret because the ESCI results are scaled in an interval from 0 to 1, where 1 is the maximum value and 0 is the minimum value [8]. A higher ESCI score means higher energy sustainability compared to other EU countries and vice versa.

After defining the conceptual idea and the main objective of the composite index to be created, the construction of the composite index consists of five main steps - selection of indicators, impact assessment, normalization, weighting and aggregation. Table 1 provides an overview of the selected indicators of energy sustainability composite index, the databases used for data selection, and the assessed impacts of each indicator. Indicators were selected based on the literature review of factors affecting energy sustainability and data availability. Data were taken from publicly available databases - Eurostat and Odysee Mure. Data was selected for 2019 as this was the latest available data for all selected indicators for all EU-27 countries.

After data selection, each indicator was divided into two groups according to its impact on ESCI - positive and negative impact. If indicators with increasing value potentially have a positive impact on energy sustainability, such as increasing the share of renewable energy sources, then the indicator has a positive impact. If indicators with increasing value have a negative impact on energy sustainability, such as an increase in emission intensity, then the indicator has a negative impact [9].

The indicators are further normalized accordingly. The min-max normalization technique is used to normalize all indicators on a scale of 0 to 1. Positive impact indicators are normalized using Eq. (1) and negative impact indicators are normalized using Eq. (2), as retrieved from [10], [11].

$$I_N^+ = \frac{I_{act} - I_{min}}{I_{max} - I_{min}} \qquad (1)$$

$$I_N^- = 1 - \frac{I_{act} - I_{min}}{I_{max} - I_{min}} , \qquad (2)$$

where I_N^+ is normalized indicator of positive impact, I_N^- is normalized indicator of negative impact, I_{act} is the actual value of an indicator for the respective country, I_{max} is the maximum value of an indicator across all countries, I_{min} is the minimum value of an indicator across all countries.

After normalizing the indicators, a weighting is applied. Following the sustainability framework which assumes that all aspects of sustainability are equally important to sustainability, the technique of equal weighting is used in this study. Finally, the ESCI is calculated using Eq. (3), aggregating all indicators into a single composite index, as retrieved from [11].

$$ESCI = \sum w \times I_N^+ + \sum w \times I_N^- , \; w = \frac{1}{n_I} , \qquad (3)$$

where ESCI is the energy sustainability composite index, w is the value of determined weight of a specific indicator, I_N^+ and I_N^- are normalized indicators, n_I is the total number of indicators.

Table 1. Selected indicators of energy sustainability composite index (ESCI).

Indicator	Description	Impact	Data source
Energy import dependency	Net energy imports divided by the gross available energy, %	-	Eurostat [12]
Share of renewable energy sources	Share of renewable energy in gross final energy consumption, %	+	Eurostat [13]
Primary energy intensity	Primary energy intensity at purchasing power parities (ppp) with climatic corrections, koe/EUR2015p	-	Odysee Mure [14]
Energy efficiency	Total energy consumption per number of inhabitants, Mtoe/population	-	Odysee Mure [15], [16]
CO_2 emission intensity	Total CO_2 emissions from fuel combustion activities per total final energy consumption (with climatic corrections), $MtCO_2$/Mtoe	-	Odysee Mure [17], Eurostat [15]
Energy poverty	Share of population unable to keep home adequately warm, %	-	Eurostat [18]

2.2 LMDI decomposition analysis

The decomposition analysis method is used to analyze how CO_2 emissions from fuel combustion have changed from 2015 to 2019. To provide the framework for decomposition analysis in this study, the Kaya identity approach is applied. Kaya identity is a mathematical identity used to explain changes in total emissions by determining four main factors-emission intensity, energy intensity, economic growth, and population growth-according to Eq (4), as retrieved from [19]. The advantage of the Kaya identity method is that it allows for the quantification of total CO_2 emissions by accounting for important determinants of emission changes. This technique is extensively employed to consider both energy and economic factors [20].

$$CO2_t = \frac{CO2_t}{En_t} \cdot \frac{En_t}{GDP_t} \cdot \frac{GDP_t}{Pop_t} \cdot Pop_t \qquad (4)$$

where $CO2_t$ are CO_2 emissions in a given period, En_t is energy consumption in period, GDP_t is gross domestic product in the period, Pop_t is population in the period. Data for the decomposition analysis using Kaya identity approach were obtained from Eurostat and Odysee Mure databases; the data sources used are summarized in Table 2.

Table 2. LMDI decomposition analysis impact factors.

Factor	Expression	Data source
Δ Emission intensity	Total CO_2 emissions from fuel combustion/ Total inland energy consumption	Odysee Mure [17], Eurostat [21]
Δ Energy intensity	Total inland energy consumption/ GDP (2015 chain linked volumes)	Eurostat [21], [22]
Δ GDP growth	GDP (2015 chain linked volumes)/ Total Population	Eurostat [16], [22]
Δ Population growth	Total population	Eurostat [16]

The Log-Mean-Divisia Index (LMDI) additive approach is used to decompose energy-related CO_2 emissions for each country, with changes in CO_2 emissions determined by changes in each separate decomposition indicator - emissions intensity, energy intensity, GDP growth, population growth - as shown in Eq. (5).

$$\Delta(CO2)t = \Delta(Emission\ intensity)t\ + \Delta(Energy\ intensity)t\ + \Delta(GDP\ growth)t\ + \Delta(Population\ growth)t = \Delta\left(\frac{CO2_t}{E_t}\right)t \cdot \Delta\left(\frac{E_t}{GDP_t}\right)t \cdot \Delta\left(\frac{GDP_t}{P_t}\right)t \cdot \Delta P_t \qquad (5)$$

According to the LDMI I additive decomposition technique, the change in each decomposition factor of CO_2 emissions is determined using Eq. (6) - Eq. (9), as retrieved from [23] and [24].

$$\Delta\, CEI = \sum_i \frac{CO2^T - CO2^0}{lnCO2^T - lnCO2^0} ln \frac{CEI^T}{CEI^0} \qquad (6)$$

$$\Delta\, EI = \sum_i \frac{CO2^T - CO2^0}{lnCO2^T - lnCO2^0} ln \frac{EI^T}{EI^0} \qquad (7)$$

$$\Delta\, GDP = \sum_i \frac{CO2^T - CO2^0}{lnCO2^T - lnCO2^0} ln \frac{GDP^T}{GDP^0} \qquad (8)$$

$$\Delta\, POP = \sum_i \frac{CO2^T - CO2^0}{lnCO2^T - lnCO2^0} ln \frac{POP^T}{POP^0} \qquad (9)$$

where CO_2 is CO_2 emissions from fuel combustion, CEI is CO_2 emission intensity, EI is energy intensity, GDP is economic growth, POP is population. Subscript 0 indicates the values of the base year, whereas subscript T indicates future values. The same notation is applicable to all variables.

3 Results

3.1. Composite index results

The goal of the Energy Sustainability Composite Index (ESCI) is to characterize the existing situation of energy sustainability based on data from 2019. The ESCI allows for cross-country comparison and identification of the main energy sustainability profiles of each country. Figure 1 depicts the energy sustainability composite index (ESCI) results. ESCI results are categorized into three primary groups: Group I consist 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 achieved 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. France's national energy sustainability is characterized by weaknesses in the share of renewable energy resources and primary energy intensity, while strengths are observed in lower energy poverty and CO_2 emission intensity. In comparison to other countries, Finland's energy sustainability is comparatively weaker due to its higher energy consumption per capita, as indicated by its energy efficiency indicator. However, Finland's energy poverty rate is relatively lower, which is its strongest aspect in terms of energy sustainability.

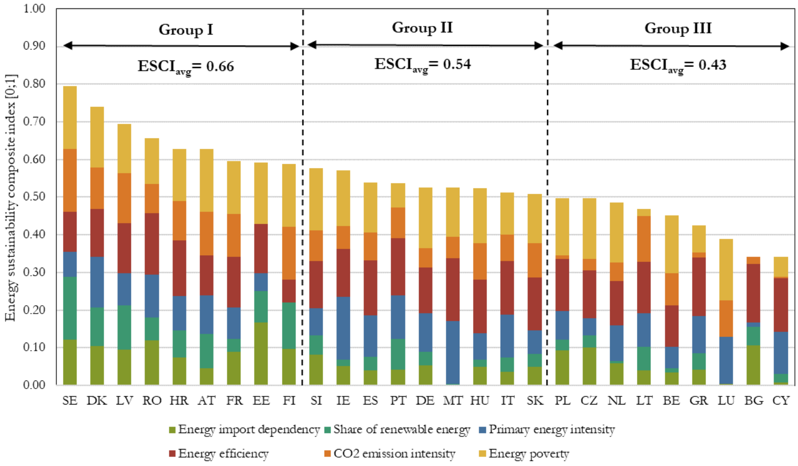

Fig. 1. Energy sustainability composite index (ESCI) results for EU-27 countries.

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 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 and the average ESCI score was 0.54. ESCI methodology enables the identification of primary strengths and weaknesses of individual countries, as well as the tracking of advancements towards attaining energy sustainability.

3.2. LMDI decomposition analysis results

The main objective of the LMDI analysis is to examine what progress has been made in energy decarbonization over the 5-year period. Figure 2 shows the results of the LMDI decomposition analysis for all EU-27 countries. The results show the progress made by the EU Member States in reducing CO_2 emissions from fuel combustion in the period from 2015 to 2019 and the main factors influencing these changes.

The results show that the majority of EU countries have succeeded in reducing CO_2 emissions from fuel combustion, moving closer to overall decarbonization targets for the economy. However, eight countries showed the opposite trend, as they experienced a slight increase in energy-related CO_2 emissions. Countries that reported an increase in CO_2 emissions from fuel combustion over the 5-year period from 2015 to 2019 are Cyprus (7.27%), Lithuania (5.87%), Hungary (4.98%), Austria (3.94%), Luxembourg (3.94%), Latvia (3.90%), Slovakia (2.13%), and Poland (1.89%). Table 3 provides an overview of the development of CO_2 emissions in these countries over the period studied, broken down by the main economic sectors - transport, households, industry, services and agriculture. The results of the LMDI analysis show that the large increase in CO_2 emissions in Cyprus is due to the large increase in economic and population growth, which has significantly increased the total demand for energy. Although a reduction in energy and emissions intensity was achieved, it was not significant enough to compensate for the increase in the overall economy. An increase in CO_2 emissions was seen in almost all sectors except industry, with the transport and services sectors being the most critical.

For Lithuania, the economic growth factor was the main reason for the sharp increase in CO_2 emissions during this period. Improvements in energy efficiency, decarbonization of energy supply, and population decline contributed slightly to offset the overall increase in CO_2 emissions, but not completely. Although Lithuania experienced significant CO_2 emission reductions in the commercial, industrial, and residential sectors during the five-year period, overall energy-related CO_2 emissions increased due to emission increases in transport and agriculture sectors.

In Hungary, economic growth was also the main cause of the increase in CO_2 emissions. Although significant improvements in energy efficiency in Hungary have helped offset some of the potential CO_2 emissions, progress in switching from fossil fuels to renewables has been extremely slow. Transport, manufacturing, and agriculture are the most critical sectors in Hungary, as they experienced a sharp increase in CO_2 emissions over the period.

In Austria, strong population growth and economic growth have increased overall CO_2 emissions. Most importantly, Austria is the only country that experienced

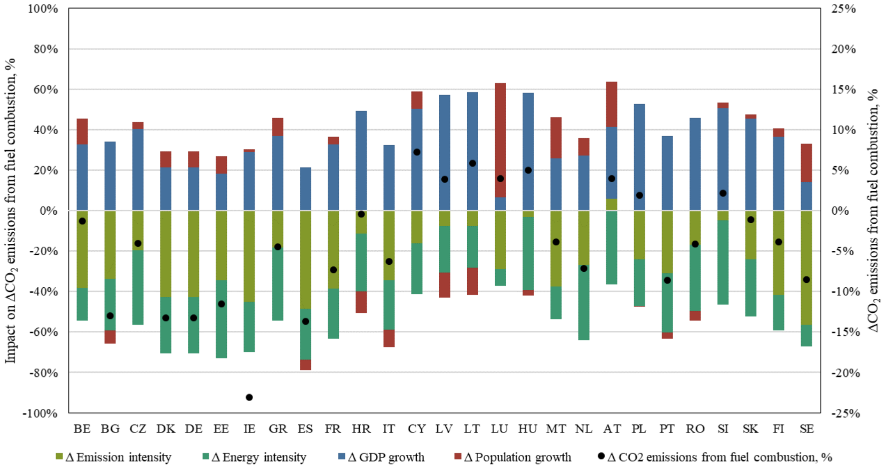

Fig.2. LMDI decomposition analysis results for changes in CO_2 emissions from fuel combustion from 2015 to 2019

an increase in overall emissions intensity during the period studied, implying that decarbonization of energy supply in Austria has not been strong enough overall. All sectors except households have seen an increase in total CO_2 emissions in Austria, with the transport and agriculture sectors being the most critical.

High population growth was the main cause of the increase in energy-related CO_2 emissions in Luxembourg, with significant reductions in emissions intensity not offsetting this growing effect. While industry, households and agriculture were able to achieve emission reductions, the increase in emissions in the service and transport sectors was more significant, leading to an increase in total CO_2 emissions in Luxembourg during the five-year period.

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, as the services, residential, and industrial sectors saw significant emission reductions.

Similar trends are observed in Slovakia and Poland, which indicated overall increase in energy-related CO_2 emissions, mainly due to increases in CO_2 emissions in transport, industry, and agriculture, while households and services sectors showed some improvements. Economic growth was the main reason for the increase in emissions in both countries, although energy efficiency and green transition improved.

The largest emission reductions from fuel combustion were achieved in Ireland (-23.05%), Spain (-13.68%), Denmark (-13.27%), Germany (-13.27%), and Bulgaria (-13.01). All of these countries achieved significant reductions in CO_2 emissions in all sectors except transport, although the increase in transport-related CO_2 emissions was slightly moderate. The common trend for these countries is significant reductions in emissions intensity, indicating strong policies toward decarbonization and green transition, while for other countries that have not achieved overall CO_2 emissions reductions, energy intensity reductions have been the most important predominant factor.

Overall, CO_2 emissions from fuel combustion in the EU decreased by 172 Mt CO_2 from 2015 to 2019. This decrease was achieved through a decrease in energy intensity (- 212.02 $MtCO_2$) and emissions intensity (-211.56 $MtCO_2$). However, the impact of economic growth (229.62 $MtCO_2$) and population growth (22.28 $MtCO_2$) prevented a greater reduction in emissions.

3.3. Combined results of ESCI and LMDI decomposition

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 results were shown for Latvia and Austria, which ranked in Group I in the ESCI but showed an increase in emissions over the period.

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.

On the other hand, countries such as Ireland and Germany, which were initially ranked lower in the ESCI, have reported significant progress in decarbonization by

Table 3. Changes in CO_2 emissions (including electricity) by sectors.

	Cyprus	Lithuania	Hungary	Austria	Luxembourg	Latvia	Slovakia	Poland
Industry	-1.2%	-7.7%	11.0%	3.3%	-5.3%	-6.6%	2.8%	2.0%
Transport	11.2%	23.4%	19.5%	7.5%	7.9%	5.7%	5.4%	34.9%
Households	5.7%	-5.7%	-0.6%	-0.8%	-15.3%	-10.7%	-4.4%	-10.3%
Agriculture	2.7%	2.6%	12.8%	6.2%	-7.0%	17.7%	1.0%	13.7%
Services	9.6%	-26.5%	-12.8%	1.5%	21.6%	-15.1%	-1.8%	-10.3%
Total	7.27%	5.87%	4.98%	3.94%	3.94%	3.90%	2.13%	1.89%

reducing CO_2 emissions from fuel combustion. This suggests that countries that initially trailed behind in demonstrating a high proportion of renewable energy resources in their total energy balances may be more motivated and driven toward a more active transition away from fossil fuels and towards renewable energy. It may be simpler for these countries to identify regions where decarbonization activities will result in substantial emission reductions.

Countries that outperformed all others are Sweden and Denmark, which are among the most energy sustainable countries in both the ESCI and LMDI, with consistent reductions in CO_2 emissions from fossil fuels. However, the worst results were shown by Cyprus and Lithuania, which ranked exceedingly low in the initial sustainability of the energy sector compared to other EU countries and encountered an increase in CO_2 emissions from fuel combustion from 2015 to 2019.

4 Conclusions

The present research introduced an innovative methodological framework for evaluating and comparing the levels of energy sustainability across different countries, as well as tracking their advancements towards green transition. Energy sustainability composite index (ESCI) 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. The results showed different profiles of energy sustainability in the 27 EU member states. The results show that there is untapped potential for all countries to enhance energy sustainability, which is reflected in all the indicators assessed.

Log-Mean Divisia Index (LMDI) decomposition analysis investigated which of the four components influenced past CO2 emissions from fuel combustion in each country – changes in emission intensity, changes in energy intensity, changes in economic growth or changes in population growth. The results revealed that although majority of EU-27 countries showed progress in reducing energy-related CO_2 emissions during the period from 2015 to 2019, a group of countries indicated negative trend by increasing emissions. Transport sector was the most critical for almost all the countries which did not show CO_2 emission reductions and pushed overall energy-related CO_2 emissions to increase. The highest energy-related CO_2 emission cuts over the 5 year period were reported by Ireland and Spain.

Sweden and Denmark with ESCI scores of 0.79 and 0.74 respectively stand out in energy sustainability and are frontrunners whose measures could serve as benchmarks for other countries. Both countries show a high level of commitment and consistent movement towards a green transition and a sustainable energy sector, which is reflected not only in the assessment of the existing situation compared to other countries, but also in the emission reduction data of the last five years.

The results revealed that countries with a higher initial level of energy sustainability, which is largely attributable to the historical development of hydropower plants, made slower progress in decarbonizing their energy systems than countries with a lower initial level of decarbonization.

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PAPER 5: TRANSITIONING TO CLEAN ENERGY: A COMPREHENSIVE ANALYSIS OF RENEWABLE ELECTRICITY GENERATION IN THE EU-27.

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MDPI

Article

Transitioning to Clean Energy: A Comprehensive Analysis of Renewable Electricity Generation in the EU-27

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Abstract: The EU power sector is under increasing pressure due to rising electricity demand and the need to meet decarbonisation targets. Member states have been active in investing in renewables and building capacity to increase their share of renewables in electricity generation. However, it is important to examine what progress each member state has made in the deployment of renewable energy for electricity generation and what factors influence gross electricity generation from renewable energy. In this study, logarithmic mean Divisia index (LMDI) analysis was used to examine the changes in EU-27 countries' gross electricity generation from renewable energy sources (RES), wind, and solar PV from 2012 to 2021. The results show that the RES deployment per capita effect and the RES share effect were the main positive factors for the total gross electricity generation from RES in the EU. In contrast, the RES capacity productivity effect and the energy intensity effect had negative contributions. Population growth had a positive influence but was less significant than the other factors. The deployment of RES per capita effect was the main factor in the overall growth of gross electricity generation from RES in Northern Europe, Central Western Europe, and Central Eastern Europe, according to comparisons between the regional groups. RES share effect was the main driver in Southern Europe. The decrease in RES capacity productivity was the second most important factor influencing the variation in the amount of energy generated by RES in Northern Europe and Central Western Europe. The results could be used to develop more effective and tailored renewable energy policies that take into account the existing main drivers of RES, wind, and solar energy in each of the EU-27 member states.

Keywords: renewable energy; LMDI; decomposition analysis; energy policy; renewable electricity; European Union; RES

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1. Introduction

The European Union (EU) has pledged to become a climate-neutral continent by 2050 [1]. In order to achieve these ambitious goals, a set of climate goals for the coming decades has been established and announced. One of the key targets is to reduce greenhouse gas emissions by at least 55% by 2030 compared to the emission levels observed in 1990 [2]. Since the energy sector accounts for more than 75% of the EU's greenhouse gas emissions [3], achieving these ambitious climate targets will necessitate the proactive implementation of measures focused on decarbonisation and enhancing energy efficiency in the energy sector [4]. To this end, the European Parliament recently 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% by 2030 [5].

As the EU strives for rapid decarbonisation and electrification of its energy system, the EU's electricity system faces significant challenges. The European Commission projects that the share of renewable energy in electricity generation should reach 55% in 2025 and 72% in 2030 [6], more than doubling its current level of 33% in 2021 [7].

Of the 2785 TWh of net electricity generation in the EU in 2021, one-third came from renewable energy sources. Of all renewable energy sources, wind energy had the highest share of electricity generation, with 13.7%, followed by hydropower with 13.3% and solar energy with 5.8%. Nuclear energy covered 25% of total net electricity generation in the EU in 2021, while almost 42% of electricity was generated from fossil fuels such as natural gas, coal, and oil [7]. Over the past decade, the EU has experienced a significant increase in the generation of renewable energy, which has been largely driven by the expansion of wind energy. The relative importance of hydropower in the total renewable electricity mix has diminished over the past two decades, as hydropower generation has remained relatively stable. Although hydropower accounted for the vast majority (90%) of electricity generated from renewable energy sources in the EU at the beginning of the 21st century, in 2021 it covered approximately 40% of the total renewable power mix [6]. It is expected that the relative significance of wind and solar PV in the total power mix will grow substantially. This projection is based on the European electrical sector's capacity to effectively incorporate considerable proportions of solar PV and wind power production [8]. The potential of wind and solar energy is still untapped in the EU. The potential varies from country to country, due to the specific characteristics of each country, such as the proportion of agricultural land, the area of the exclusive economic zone and population density. In addition, the wind and photovoltaic potential in the individual countries is determined by the capacities already installed. According to a study by [9], Germany has relatively the lowest development potential due to its large installed capacities, whereas Latvia has enormous development potential due to its low installed capacities [9].

In the future, as smart energy systems continue to evolve, there will be a substantial increase in the electrification of end-use consumption. This shift will be driven by the growing adoption of electrical appliances like heat pumps and cooling systems, as well as efforts to decarbonise transportation by transitioning to vehicles that utilize electricity as an alternative fuel source [10]. The EU's electricity sector is expected to grow significantly in the coming years [11], as it is expected that electricity demand in the EU will increase by at least 32% by 2050 compared to its current levels [12]. Furthermore, the REPowerEU 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 role of renewable energy use in electricity generation is highlighted in the REPowerEU plan, which has set a target for the share of renewable energy in gross final electricity consumption to reach 69% by 2030 [14], compared to only 37.6% of total electricity demand in the EU from renewable sources in 2021 [15].

To reach these targets a package of policies and regulatory frameworks has been put in place to encourage renewable energy production in the EU. The Renewable Energy Directive, established in 2009, mandated that by 2020, 20% of the EU's energy consumption must come from renewable sources [16]. The directive outlined various strategies, such as support and collaboration measures, to achieve these objectives. In addition, it confirmed each country's present national renewable energy goals. Progress towards these objectives was evaluated every 2 years. As part of the "Clean energy for all Europeans" package, the revised Renewable Energy Directive was introduced in 2018 to maintain the EU's leadership in renewables, with the goal of deriving at least 32% of final energy consumption from renewables by 2030. The directive required EU member states to implement it as national law by June 2021. Three additional amendments to the Renewable Energy Directive were made between July 2021 and March 2023 in response to the "Fit for 55" package and REPowerEU plan, which was introduced in response to the Russian invasion of Ukraine. The amendments continued to increase the overall renewable energy target to 42.5% by 2030 in order to accelerate the phase-out of Russian fossil fuels and encourage the development and deployment of renewable hydrogen [17]. Efforts have been undertaken to establish a shared framework for the advancement of sustainable cross-border energy infrastructure, with the aim of facilitating the deployment of renewable energy across all member states of the European Union. EU Regulation 2022/869 amending Directive 2019/944 establishes EU rules for trans-European energy networks that focus on interconnecting the energy infrastructure of EU countries [18]. The regulation establishes the means by which member states, regulatory authorities, and transmission system operators can work together to establish a fully interconnected internal market for electricity that enhances the incorporation of electricity from renewable sources, free competition, and supply security [19]. The binding legislation emphasises the significance of offshore wind projects while explicitly excluding European Union support for forthcoming natural gas developments. It aims to facilitate the incorporation of renewable energy sources and emerging clean energy technologies into the energy system. Additionally, it seeks to establish connections between regions that are presently disconnected from European energy markets, enhance existing cross-border interconnections, foster collaboration with partner nations, and suggest strategies to streamline and expedite permitting and authorization processes [17].

Following the course set by the EU, member states have indeed been actively investing in renewable energy and installing capacities to increase their share of renewable energy in electricity generation. However, it is important to examine what progress each member state has made in the deployment of renewable energy for electricity generation and what factors influence gross electricity generation from renewable energy. The purpose of this paper is to investigate the primary drivers of change in electricity generation from renewable energy sources (RES) and to determine which factor has had the greatest influence on these changes over the past decade. This paper examines what progress member states have made in increasing the amount of electricity generated from RES and how EU-27 countries compare. This study utilized logarithmic mean Divisia index (LMDI) decomposition analysis to examine changes in EU-27 countries' gross electricity production from RES, wind, and solar PV from 2012 to 2021. Further analysis was conducted to compare and contrast the differences and similarities between the four groups of regional electricity markets in the European Union: Northern Europe, Central Western Europe, Central Eastern Europe, and Southern Europe. The findings could be used to develop more effective and tailored policies for renewable energy, taking into account the existing primary drivers of RES, wind, and solar PV energy in each of the EU-27 member states.

The structure of the paper is as follows: Section 2 describes previous studies analyzing the primary drivers of RES electricity production and research on LMDI applications; Section 3 presents the methodologies and data used in this study; Section 4 describes the results and discusses the key findings; and Section 5 summarizes the major conclusions of the paper.

2. Literature Review

Different methods and approaches are employed to analyse the primary factors influencing the utilization of renewable energy in electricity generation. A study by [20] investigated the factors affecting the technological innovation of different renewable energy sources (wind, solar, geothermal, ocean, biomass) using a dynamic panel approach. A number of explanatory variables were selected, such as renewable energy tariff, R&D intensity, RES installed capacity, electricity consumption, and electricity price. The findings revealed that electricity consumption was the most important influencing factor for all RES sources and wind energy, while the effect was weaker for solar energy and biomass. R&D intensity proved to be the most influential factor for biomass [20].

In an empirical investigation conducted by [21], the objective was to assess the influence of economic and social factors on the adoption of renewable energy using the random effect of the generalized least squares method [21]. In their study, [22] employed the autoregressive distributed lag (ARDL) bounds testing cointegration approach to examine the primary determinants of renewable energy sources consumption in Malaysia. The researchers analysed the long-term relationships between RES consumption, carbon dioxide emissions, economic growth, trade openness, and foreign direct investment using time series data spanning from 1980 to 2015. The study revealed that the most significant variables contributing to the consumption of renewable electricity were economic growth and foreign direct investment [22].

In addition to quantitative indicators that assess technoeconomic parameters of renewable energy deployment, there are studies that examine the significance of climate policy quality and institutional capacity. For example, a study by [23] employed a Markov-switching equilibrium approach in their investigation of the most influential factors in green energy investment. The authors focused on two primary factors that determine investment in renewable energy: the exploitation of natural resources and the uncertainty of climate policy. The study suggested that there should be robust governance on the use of natural resources, which would encourage resource efficiency, since sustainable natural resource exploitation and a growing proportion of renewable energy are the primary drivers of long-term sustainable development. Moreover, the government should play a crucial role in eliminating uncertainty in climate and energy policy by implementing long-term economic measures. In addition, international organisations such as the World Bank and others should provide effective support for the development of energy policies in developing nations [23]. Moreover, another study emphasized the role of policy strengthening where [24] examined the structural changes connecting economic growth and institutional quality in terms of CO_2 emissions and energy consumption. The study revealed that institutional quality has a significant and positive effect on CO_2 emissions, and that increasing economic growth decreases CO_2 emissions. The study suggests that Pakistan should continue its economic development policies in order to promote the green transition. In addition, the study argues that institutional quality and government efficiency must be considerably enhanced by strengthening the policy and regulatory framework and environmental legislation and reducing corruption in order to transition to a more sustainable economy in the future [24].

Prior research on green growth and energy transition factors in the EU region focused on analysing the factors that influence energy-related CO_2 emission reductions. Using the generalised method of moments (GMM), ref. [25] analysed the impact of GDP, renewable energy growth, energy demand, population, and effective capital on EU-27 CO_2 emissions from 1990 to 2019. The authors determined the "effective capital" indicator, which represents the relationship between the physical machinery used to produce products and energy consumption. The study found that high economic growth that is fuelled by high consumption of fossil fuels has a direct impact on rising carbon emissions. As a result, a rapid transition to renewable energy should be encouraged, as it has been shown to have a significant impact on reducing CO_2 emissions. Effective capital and energy use are observed to increase CO_2 emissions, while capital and population size decrease carbon emissions in the European Union [25]. A study by [26] analysed the impact of renewable energy resources and nuclear energy on the reduction of carbon emissions in 22 EU member states between 1992 and 2019. The study revealed that an increase in renewable energy reduced CO_2 emissions per capita in the European Union by a significant amount. In terms of EU carbon emission reductions, the results of the study also indicated that nuclear power was not significant in any of the studied countries. The study revealed that energy consumption per capita also had an increasing influence on carbon emissions; consequently, the authors recommended that the EU implement more stringent energy efficiency policies [26]. In their study on the primary determinants of CO_2 emissions from electricity generation in the EU, [27] emphasized the need for disaggregating renewable energy types in decomposition studies. Ref. [27] discovered that year-to-year fluctuations in the quantities of hydro energy and nuclear energy impact the overall evaluation of renewable energy expansion in the EU. The EU has witnessed a constant increase in solar and wind energy over the past decade; therefore, there is a need for a more in-depth investigation into the primary factors influencing these increases [27].

There are a few studies investigating the factors influencing the growth of renewable electricity generation in the EU. Most of them focus on the impact of energy policies on the targets of RES. A study conducted by [28] used the pool mean group autoregressive distributive lag model (PMG-ARDL) to investigate how investment in R&D correlates with the expansion of renewable and non-renewable energy resources in the EU. The results show that renewable energy has a bidirectional relationship with R&D expenditure, which means that the economy develops through the use of renewable energy resources, thus driving the future growth of renewable energy resources [28]. A study by [29] investigated the effect of various policy measures on the deployment of renewable energy in power generation in the EU. Different levels of harmonisation and the use of a feed-in tariff, a feed-in premium, or a quota system with a classification scheme had comparable effects on the deployment of renewable energy in electricity generation [29]. In a study conducted by [30], an analysis was performed to assess the influence of nine socioeconomic parameters on the installed capacity of energy derived from renewable sources in 10 European Union (EU) member nations. The parameters included in this study encompassed the installed capacity of electricity derived from renewable sources, population size, inflation rate, GDP per capita, unemployment rate, energy dependence, net imports of electricity, income inequality, total electricity consumption, and electricity prices. The findings indicated that all socioeconomic factors examined had a significant impact on the endogenous variables [30]. The study conducted by [31] examined the advancements made by Northern European nations in the use of renewable energy sources for the purpose of power production. The authors conducted a comparative analysis between the actual progress made in the development of renewable power and the intended future targets. The results of the study revealed disparities in the implementation of various renewable energy power generation technologies. Certain countries demonstrated lower levels of proficiency in adopting newer renewable energy sources, such as wind power, but compensated for this deficiency by excelling in more established technologies, such as biomass. This trend raises concerns, as the utilization of all available technologies will be crucial in achieving the European Union's decarbonisation objectives [31].

There are also a number of review papers that have attempted to identify the main drivers, barriers, and trends in the deployment of renewable energy in the energy sector. For example, ref. [32] reviewed the main drivers and barriers affecting the deployment of concentrated solar power (CSP) in the EU. The higher added value of CSP was recognised as the main driver, with policy incentives in the form of R&D and deployment support also considered important. High initial investment and policy uncertainty were identified as the main barriers. The importance of R&D expenditure was also addressed in a study by [33], who argued that in the energy sector, policymakers should prioritize increased investment in innovative technologies, expenditure on renewable energy R&D along with improved economic performance, and collaboration on the development of environmental technologies [33]. Another review paper by [34] explored the obstacles hindering the adoption of wind and solar PV technologies in electricity supply systems. The research highlighted several significant barriers, including insufficient financial resources, limited grid capacity, delays in obtaining building permits, resistance from local communities towards wind farm construction, and the absence of a stable institutional framework.

However, review papers fail to estimate and quantify RES development patterns, which can be effectively accomplished by applying decomposition analysis. There exist several decomposition analysis techniques, such as the logarithmic mean Divisia index (LMDI), Laspeyres index, Fisher ideal index [35], and others, but the LMDI approach is one of the most commonly used in energy research because of its ease of application and interpretation of results.

One of the most frequently employed applications of the logarithmic mean Divisia index in the field of energy research relates to the examination of variations in carbon dioxide emissions caused by energy sources. A study by [36] combined the extended Kaya identity with the logarithmic mean Divisia index decomposition method to investigate changes in energy-related carbon emissions in China. The authors demonstrated the practical application of the results of the LMDI decomposition analysis by showing real cases of LMDI application in energy and climate policy, using examples from China, and setting out recommendations for CO_2 reductions [36].

In their study, ref. [37] applied the LMDI technique to investigate the main factors affecting changes in CO_2 emissions in the 23 countries with the highest use of renewable energy, including 12 European countries, with a focus on six main factors: the intensity of carbon trading, the impact of fossil fuel trading, the intensity of fossil fuels, the productivity of renewable energy sources, the effect of electricity financial power, and the impact of financial development. The changes were examined for the period from 1985 to 2011. For European countries, renewable energy productivity effects were found to be the primary contributors to increases in CO_2 emissions, while electricity financial power effects contributed to decreases.

Changes in CO_2 emissions by applying LMDI were also studied by [38], who investigated the causes of the global increase in emissions over the last two decades. The results of the study indicate that the primary driver of CO_2 emissions during the period spanning from 1997 to 2015 was economic growth. The factor of population growth also contributed to the increase in emissions, with a more pronounced effect observed in countries with lower income levels. The authors of this study found that total emissions would have been half as much if there had been no energy efficiency and decarbonisation measures in the past. The authors propose that there should be a more expedited reduction of CO_2 emissions in highly industrialised nations, accompanied by sufficient assistance to developing countries as they transition towards a more environmentally sustainable economy [38].

Another study [39] investigated the factors that influenced the variations in the levels of energy-related CO_2 emissions in four categories (eastern, western, northern, and southern) of 21 European countries in two periods—before (1999–2004) and after (2005–2010) the Kyoto Protocol. The study used LMDI decomposition analysis to decompose CO_2 emission changes into six primary factors: the carbon intensity effect, the energy mix effect, the energy intensity effect, the average renewable capacity productivity effect, the capacity of renewable energy per capita effect, and the population change effect. The study concluded that the consumption of renewable energy was also influenced by country-specific factors such as the scale and structure of the economy.

LMDI was also used to study changes in carbon intensity levels and investigate the key drivers behind these changes. For example, a study by [40] built a model combining index decomposition analysis (IDA) and the LMDI approach to analyse and compare the driving factors of changes in aggregate carbon intensity between different regions of China over a 14-year period. The main decomposition factors used in the analysis were installed capacity mix, thermal capacity factor, and total capacity factor. The results showed that overall carbon intensity decreased after 2015 due to a rebound in carbon intensity in five regions.

In the field of renewable energy, LMDI was used to study renewable energy consumption patterns. A study by [41] examined the primary drivers of wind energy consumption by employing LMDI decomposition for 17 key wind energy-consuming nations, including Denmark, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, and Sweden, from the EU. Increasing RES share had the greatest effect on wind energy growth, while decreasing energy intensity reduced wind energy consumption. Based on identified compound annual growth rates for wind energy consumption in the respective countries, the author developed three distinct forecasting scenarios. The study concluded that the use of wind energy will increase in the future if the RES share of the overall energy mix continues to rise, which is highly dependent on robust energy policies aimed at accelerating the decarbonisation of the energy sector [41].

Another study [42] used the extended Kaya identity equation with the LMDI approach to examine the influence of the five key factors affecting renewable energy consumption in 32 BRI countries: structural changes, changes in energy intensity, changes in decarbonisation, changes in carbon emissions, and changes in population distribution and growth. The study shows that energy structure was the main reason for the increase in RES consumption, while the effect of energy intensity reduced the overall consumption of RES [42].

Using the LMDI approach, the study conducted by [43] examined the fluctuations in wind and solar power consumption in China between 2015 and 2018, focusing on six key factors: transmission structure, generation proportion, power self-sufficiency, resource development, resource utilisation, and power consumption. The study found that the electricity mix effect and the resource development effect have played significant roles in the evolution of the wind and solar power consumption rate, but their effects have been diminishing [43].

A study by [44] investigated the evolution of renewable energy generation in the European Union from 2000 to 2020 using the LMDI decomposition analysis method. The study identified four primary factors for analysing variations in renewable energy production: RES share, energy intensity, population, and activity. The study discovered that RES share and energy efficiency had the greatest impact on variations in RES generation over the course of the study period.

A study by [45] explored the spatial-temporal heterogeneity and dynamic evolution of renewable electricity deployment in the EU from 2001 to 2017. LMDI decomposition analysis was applied to investigate changes in electricity generation determined by seven factors: technological structure effect, generation efficiency effect, investment structure effect, investment gap effect, energy structure effect, energy intensity effect, and economic scale effect. The study found that the investment structure effect was the main driver of the penetration of RES, while efficiency improvements reduced renewable electricity generation [45].

LMDI was also applied to investigate the RES innovation trends and efforts in increasing RES efficiency. In their research, [46] employed an extended LMDI approach to explore the effects of nine key factors on patenting in renewable energy technologies, namely the prioritization of specific technologies, the significance of specific technology in relation to all patents, the effectiveness of patents associated with research and development expenditures, the proportion of R&D spending in the gross domestic product, the productivity of renewable energy sources, the share of renewable energy, energy intensity, carbon productivity, and the impact of carbon emissions. The authors concluded that the number of patents for a given renewable energy technology increases, along with other factors, when priority is given to innovation in a specific technology, the efficiency of R&D spending increases, and the share of RES increases [46]. A study by [47] analysed the underperformance of PV-generated electricity in China compared to PV-generated power in the US. The LMDI approach was applied to quantify solar electricity production in China and the US with three main factors: estimated annual peak sun hours, efficiency, and curtailment ratio. The study found that solar system efficiency was the key factor that differentiated China's PV performance from that of the US. Efficiency was lower because of the lower quality of PV panels, their maintenance and more pollution, which negatively affected the efficiency of PV systems in China [47].

There is no universally accepted method for analysing the RES generation levels and estimating the RES impact factors. However, previous studies have shown that decomposition analysis, and especially the LMDI approach, is widely used in the field of energy research, as it provides results that are easy to interpret and apply for better policymaking.

Based on the literature review, it can be concluded that there has been limited research examining the growth determinants of renewable electricity in the EU over the past 5 years. Prior research in the EU focused primarily on employing an econometric approach and examining the correlations between various variables; however, the majority of this research is out of date. Out of the existing research employing the LMDI approach in the EU, studies are typically limited to applying the Kaya identity approach; however, a number of other factors, such as capital productivity, rate of decarbonisation, and others, should be included. In addition, there is a lack of research on the disaggregation of renewable energy resources, with a focus on wind and solar development, which has seen a significant increase over the past decade. Most research covers the entire aggregated energy sector, with limited attention directed towards an exclusive examination of electricity generation.

This study focuses on the power generation sector rather than the energy sector as a whole to enable a more comprehensive understanding of its role and importance in the pursuit of long-term sustainability, particularly given the significant impacts expected from future electrification and decarbonisation targets. The study develops a novel LMDI decomposition approach, decomposing gross electricity generation from RES into five main factors: RES share effect, energy intensity effect, RES capacity productivity effect, RES deployment per capita effect, and population growth effect. The study examines the main drivers of total gross electricity production by disaggregating renewable energy resources and analysing the dynamics of production changes in wind and solar energy separately. The paper provides a comprehensive analysis of the most recent progress in renewable energy use in electricity generation over the last decade in the context of the EU's path towards climate neutrality.

3. Methods and Data

The study applied the logarithmic mean Divisia index (LMDI), using an additive approach to decompose the changes in production values of gross electricity from renewable energy sources over the 10-year period from 2012 to 2021. Given that the EU's long-term climate and energy targets span a period of 10 years, this study specifically chose a 10-year range to examine the extent of changes and progress made towards these established targets. Five main decomposition factors were determined to construct the LMDI for changes in electricity generation from RES over the years: changes in the share of RES in total electricity generation, changes in the energy intensity of electricity generation, changes in RES capacity productivity, changes in the per capita installed capacities of RES, and changes in population growth.

LMDI decomposers were determined based on a combination of the studies by [39,44], which analysed changes in energy-related CO_2 emissions and the development of RES generation in Europe using the LMDI decomposition approach. Equation (1) demonstrates the identity between the LMDI factors that determine the changes in the total amount of energy produced by RES, adapted from [39,44].

$$RES = \sum_i RES_i = \sum_i \frac{RES}{EN}\frac{EN}{GDP}\frac{GDP}{RCAP}\frac{RCAP}{POP}POP = \sum_i RSH_i EI_i RPR_i RD_i POP_i \quad (1)$$

where *RES* denotes gross electricity production from renewables, *EN* denotes total gross electricity production, *GDP* denotes gross domestic product, *RCAP* denotes electricity production capacities for renewables, *POP* denotes total population, *RSH* denotes RES share effect, *EI* denotes energy intensity effect, *RPR* denotes RES capacity productivity effect, and *RD* denotes RES deployment per capita effect.

According to the additive decomposition method, variations in RES-produced electricity are further determined by variations in each LMDI decomposer, as shown in Equation (2). The additive approach was chosen instead of the multiplicative approach to allow a more comprehensive representation of the changes in RES in the EU and an uncomplicated interpretation of the results. The additive approach calculates the difference in the amount of change when comparing two time periods [48], whereas the multiplicative approach calculates the ratio of change [49]. The decomposition analysis results in the additive approach are typically expressed in physical units, whereas in the multiplicative approach, the results are expressed as indices [50].

$$\Delta RES = RES^T - RES^0 = \Delta RES_{rsh} + \Delta RES_{ei} + \Delta RES_{rpr} + \Delta RES_{rd} + \Delta RES_{pop} \quad (2)$$

The changes in the individual LMDI decomposers are calculated using Equations (3)–(7), which were adapted from [51].

$$\Delta RES_{rsh}=\sum\nolimits_i \frac{RES^T-RES^0}{lnRES^T-lnRES^0} ln\frac{RSH_1^T}{RSH_1^0} \quad (3)$$

$$\Delta RES_{ei}=\sum\nolimits_i \frac{RES^T-RES^0}{lnRES^T-lnRES^0} ln\frac{EI_1^T}{EI_1^0} \quad (4)$$

$$\Delta RES_{rpr}=\sum\nolimits_i \frac{RES^T-RES^0}{lnRES^T-lnRES^0} ln\frac{RPR_1^T}{RPR_1^0} \quad (5)$$

$$\Delta RES_{rd}=\sum\nolimits_i \frac{RES^T-RES^0}{lnRES^T-lnRES^0} ln\frac{RD_1^T}{RD_1^0} \quad (6)$$

$$\Delta RES_{pop}=\sum\nolimits_i \frac{RES^T-RES^0}{lnRES^T-lnRES^0} ln\frac{POP_1^T}{POP_1^0} \quad (7)$$

where superscript T stands for indicator value in the future year and 0 for indicator value in the initial year, and subscripts *rsh*, *ei*, *rpr*, *ri*, *pop* denote the changes in the share of RES, energy intensity, RES capacity productivity, per capita installed capacities of RES, and population growth, respectively.

All data used for LMDI decomposition analysis construction were retrieved from Eurostat. Table 1 summarises the data values used in the study and the list of data sources. All values of the selected variables were collected for all 27 EU countries. The data series covered the period from 2012 to 2021, i.e., the most recent data available at the time this study was conducted.

Table 1. Description of the data values used in the study and list of data sources.

Notation	Description	Source
RES	Gross electricity production from renewables and biofuels, GWh	[52]
EN	Total gross electricity production, GWh	[52]
GDP	Gross domestic product at market prices, chain linked volumes, MEUR	[53]
RCAP	Electricity production capacities for renewables, MW	[54]
POP	Total population, number of inhabitants	[55]
W	Gross electricity production from wind, GWh	[56]
PV	Gross electricity production from solar photovoltaic, GWh	[56]
WCAP	Electricity production capacities for wind, MW	[54]
PVCAP	Electricity production capacities for solar PV, MW	[54]

This study extends the LMDI decomposition analysis to examine how wind and solar PV installations, which have experienced significant growth in the past decade, contribute to the overall increase in renewable energy sources. Equations (8) and (9) are used to examine in more detail the changes in electricity generation from wind and solar PV, adapted from [39,44].

$$W=\sum\nolimits_i W_i=\sum\nolimits_i \frac{W}{RES}\frac{RES}{EN}\frac{EN}{GDP}\frac{GDP}{WCAP}\frac{WCAP}{POP}POP=\sum\nolimits_i WSH_iRSH_iEI_iWPR_iWD_iPOP_i \quad (8)$$

$$PV=\sum\nolimits_i PV_i=\sum\nolimits_i \frac{PV}{RES}\frac{RES}{EN}\frac{EN}{GDP}\frac{GDP}{PVCAP}\frac{PVCAP}{POP}POP=\sum\nolimits_i PVSH_iRSH_iEI_iPVPR_iPVD_iPOP_i \quad (9)$$

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

For further decomposition of Equations (8) and (9), the same calculation method is used as for Equations (3)–(7). Table 2 summarizes LMDI decomposition analysis decomposers used in this study to decompose the changes in production values of gross electricity from RES, wind, and solar PV over a 10-year period.

Table 2. Description of LMDI decomposition analysis decomposers.

Notation	Factor	Unit	Factor Calculation
RSH	RES share effect	%	Gross electricity production from renewables (GWh)/Total gross electricity production (GWh)
EI	Energy intensity effect	GWh/MEUR	Total gross electricity production (GWh)/Gross domestic product (MEUR)
RPR	RES capacity productivity effect	MEUR/MW	Gross domestic product (MEUR)/Electricity production capacities for renewables (MW)
RD	RES deployment per capita effect	MW/population	Electricity production capacities for renewables (MW)/Population (number)
WSH	Wind share effect	%	Gross electricity production from wind (GWh)/Gross electricity production from renewables (GWh)
WPR	Wind capacity productivity effect	MEUR/MW	Gross domestic product (MEUR)/Electricity production capacities for wind (MW)
WD	Wind deployment per capita effect	MW/population	Electricity production capacities for wind (MW)/Population (number)
PVSH	Solar PV share effect	%	Gross electricity production from solar PV (GWh)/Gross electricity production from renewables (GWh)
PVPR	Solar PV capacity productivity effect	MEUR/MW	Gross domestic product (MEUR)/Electricity production capacities for solar PV (MW)
PVD	Solar PV deployment per capita effect	MW/population	Electricity production capacities for solar PV (MW)/Population (number)

The RES share effect (*RSH*) represents the extent of decarbonisation of the country's total electricity production. The energy intensity effect (*EI*) defines the impact of energy efficiency improvements; a decrease in energy intensity indicates that the overall energy efficiency of electricity production has increased, as fewer energy resources were required to produce a unit of economic output. The RES capacity productivity effect (*RPR*) defines the changes in economic output generated per installed electricity capacity of renewable energy technologies such as wind turbines, solar PV, hydropower plants, and biofuel stations. The RPR effect outlines the impact on economic growth per installed RES capacity. The wind capacity productivity effect (*WPR*) describes the changes in generated economic output per installed wind turbine electricity capacities, whereas the solar PV capacity productivity effect (*PVPR*) describes the changes in generated economic output per installed solar PV electricity capacities. The RES capacity productivity effect was also utilised as one of the LMDI decomposers in a study conducted by [39], which defined the RES capacity productivity factor as the ratio between GDP and renewable capacity. A similar approach was employed in the study by [37], which determined the productivity of electric power from renewable sources—an indicator measuring changes in income or economic value per unit of electric power derived from renewable energy resources— thereby capturing the income effect of electric power generated from renewable energy sources. The RES deployment per capita effect (*RD*) represents the increase in installed RES capacities per number of inhabitants in the country, thus indicating the rate of green transition in electricity production. The wind share effect (*WSH*) represents the share of wind in the total amount of electricity produced from renewables. Similarly, the solar PV share effect (*PVSH*) represents the proportion of solar PV in the total RES mix used for electricity generation.

4. Results and Discussion

4.1. Renewable Energy Sources Profile for Electricity Generation in the EU-27 Countries

Initially, existing energy profiles of EU-27 countries were analyzed to gain a comprehensive understanding of their main characteristics and to facilitate country comparisons. Two key indicators were collected and compared: per capita electricity generation from renewable energy sources and the distribution of different RES in gross electricity generation. This analysis served as a foundation for a more in-depth examination and explanation of the LMDI analysis results, allowing for more accurate interpretations and insights into the data.

Figure 1 shows the per capita RES electricity generation rates for all EU-27 countries in 2012 and 2021. Average per capita electricity generation from RES in the EU-27 increased from 1.9 MWh in 2012 to 2.7 MWh in 2021. Sweden (11.2 MWh), Finland (6.9 MWh) and Austria (6.3 MWh) showed the highest per capita electricity generation from RES in 2021, while Malta (0.5 MWh), Hungary (0.7 MWh), and Poland (0.8 MWh) showed the lowest. It can be observed that the majority of countries increased their renewable electricity generation per capita, with the exception of Latvia and Austria. The highest increases were observed in Malta, Cyprus, Hungary, Greece, Lithuania, and Croatia. The graph shows that the strongest increases were observed in the countries where per capita electricity generation from RES was originally lowest in 2012.

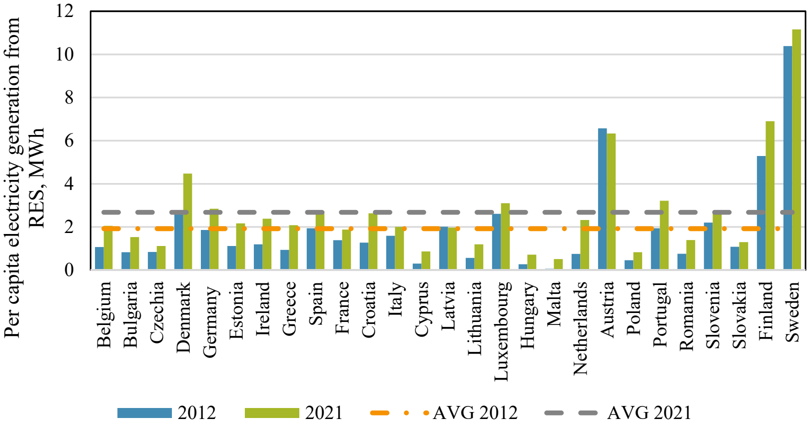

Figure 1. Per capita RES electricity generation, MWh, based on data from [55,56].

Figure 2 illustrates the share of different renewable energy sources (hydro, wind, solar, biomass, and others) in gross electricity generation in 2020, based on data from [57].

Countries with the highest share of hydropower in gross electricity generation from RES were Slovenia (88%), Latvia (74%), Croatia (70%), with the highest share of wind energy—Ireland (86%), Denmark (69%), Lithuania (55%), with the highest share of solar energy—Malta (98%), Cyprus (51%), Netherlands (27%), Belgium (23%), and with the highest share of biofuels—Estonia (64%), Finland (32%), Hungary (30%).

The most diversified profiles of gross electricity generation from RES were found in the Czech Republic, Luxembourg, Italy, and the Netherlands. In the EU-27, wind energy (36%) and hydropower (33%) were the main sources of gross electricity generation from RES, followed by solar energy (14%), other renewables (8.4%), and solid biofuels (8%).

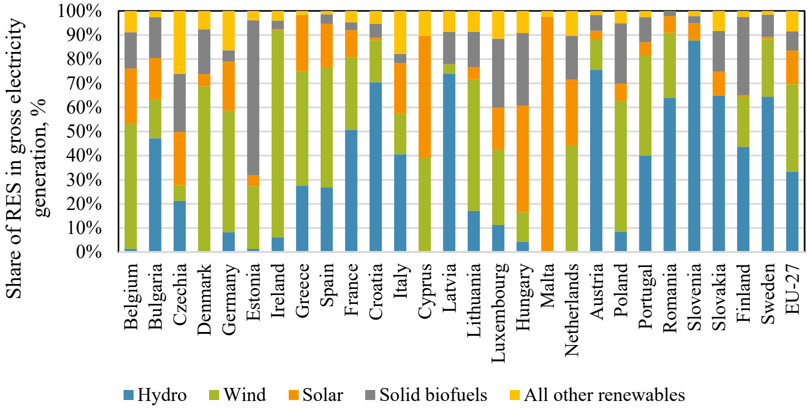

Figure 2. Use of different RES for gross electricity generation in 2020, based on data from [57].

4.2. LMDI Decomposition Analysis Results

Figure 3 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. Figure 3 excludes Malta for more comprehensive representation purposes.

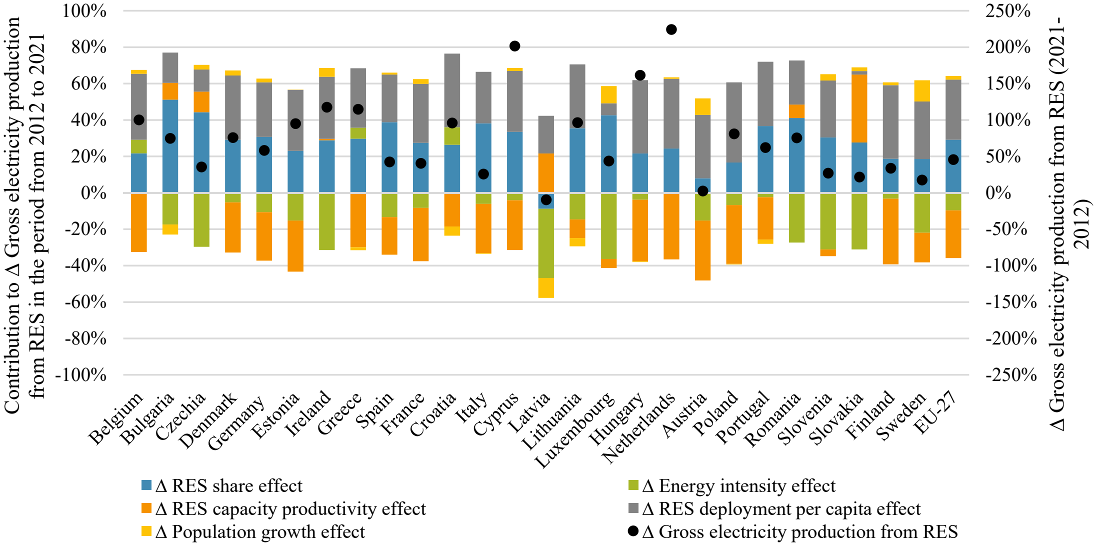

Figure 3. Contribution of LMDI factors to changes in gross electricity production from RES over the period from 2012 to 2021.

By 2021, the highest increases in gross electricity generation from RES compared to 2012 levels were observed in Malta (926%), the Netherlands (224%), Cyprus (202%), Greece (115%), and Belgium (100%). In terms of absolute increases in gross electricity generation from RES, the leaders were Germany with an increase of 87 TWh, Spain with an increase of 38 TWh, France with an increase of 37 TWh, and the Netherlands with an increase of 28 TWh. Table 3 summarizes the LMDI results for the changes in gross electricity generation from RES from 2012 to 2021 in absolute terms, expressed in GWh.

Table 3. LMDI analysis results for changes in gross electricity production from RES from 2012 to 2021, GWh.

	ΔRES Share Effect	**ΔEnergy Intensity Effect**	**ΔRES Capacity Productivity Effect**	**ΔRES Deployment per Capita Effect**	**ΔPopulation Growth Effect**	**ΔGross Electricity Production from RES**
Belgium	7326	2519	−11,005	12,275	718	11,833
Bulgaria	4271	−1452	771	1392	−467	4515
Czechia	3412	−2289	870	933	201	3126
Denmark	9533	−1719	−9029	11,578	897	11,259
Germany	105,078	−36,434	−91,404	102,899	6840	86,978
Estonia	2421	−1609	−2949	3524	15	1402
Ireland	5006	−5456	133	5908	841	6432
Greece	9550	1935	−9609	10,519	−540	11,856
Spain	46,536	−16,000	−24,791	31,357	1287	38,389
France	40,245	−12,168	−43,001	47,612	3840	36,528
Croatia	2595	948	−1824	3981	−495	5205
Italy	28,085	−4493	−19,887	20,857	−333	24,228
Cyprus	468	−57	−382	466	23	518
Latvia	−222	−960	544	522	−276	−392
Lithuania	1410	−583	−408	1397	−181	1635
Luxembourg	1480	−1262	−175	227	329	599
Hungary	3877	−690	−6076	7237	−78	4269
Malta	176	−5	−187	221	33	238
Netherlands	25,370	−15	−38,157	39,938	855	27,991
Austria	2867	−5515	−11,892	12,573	3287	1320
Poland	10,913	−4419	−21,259	28,943	−155	14,023
Portugal	10,596	−689	−6747	10,187	−668	12,678
Romania	11,450	−7629	2055	6750	−1146	11,480
Slovenia	1218	−1248	−148	1254	141	1216
Slovakia	924	−1040	1245	65	67	1262
Finland	8400	−1470	−16,197	18,168	714	9615
Sweden	13,661	−16,177	−11,968	23,254	8573	17,343
EU-27	356,645	−117,979	−321,478	404,033	24,323	345,544

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 preceding decade, driven by an exceptional surge in water inflow into the Daugava River, where the main hydropower plants are situated in the country.

Austria showed limited progress in increasing the proportion of gross electricity generation from renewable energy sources when comparing levels in 2012 to those in 2021, with a modest growth of only 2.4%. Similarly to Latvia, Austria experienced record-high hydropower production in 2012. In both countries, hydro energy constitutes a significant portion of the overall electricity production mix, making them more exposed to fluctuations in water inflows caused by changes in weather conditions. This observation suggests that countries with lower levels of RES diversification may be more exposed to significant fluctuations in production quantities. These findings are in line with the results of a study by [27], who argued that annual fluctuations in the amount of hydro energy have a significant impact on the total amount of electricity generated from RES in national power generation plants.

Moderate progress in the relative increase in electricity generation from RES was observed for Sweden (17.6%), Slovakia (21.7%), Italy (25.7%), and Slovenia (26.9%). It is noteworthy that Sweden, Austria, and Latvia emerged as prominent nations with a significant share of renewable energy sources in their electricity generation in the year 2021. This discovery suggests that countries that have already achieved a high level of renewable energy sources penetration in their electricity production have experienced slower advancements in the deployment of RES. In contrast, Denmark, Portugal, and Croatia have demonstrated both an initially higher proportion of renewable energy sources in their electricity generation and significant advancements in increasing this share over time [57].

The results of the LMDI analysis show that several factors contributed to the changes in gross electricity generation from RES for the EU-27 countries. 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. In the EU, total gross electricity generation from RES increased by 45.7% during the period from 2012 to 2021. In total, 11 countries reported a change in gross electricity generation from RES below the EU level during this period—Czech Republic (35.5%), Spain (42.4%), France (40.5%), Italy (25.7%), Latvia (−9.5%), Luxembourg (43.7%), Austria (2.4%), Slovenia (26.9%), Slovakia (21.7%), Finland (33.7%), and Sweden (17.6%).

The 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. The RES capacity productivity effect measures the amount of GDP produced per installed capacity. However, if the installed capacities are currently low and not experiencing significant growth, it indicates untapped potential for renewable energy capacity installations in these countries. It is important to note that the RES capacity productivity effect incorporates the speed of economic growth, which in turn also has a direct impact on total electricity demand. If economic growth slows down, this could also indicate a lower total electricity demand and a lower need to generate the amount of electricity required to meet this demand. On the other hand, faster GDP growth has a significant impact on total electricity demand and leads to an increase in electricity generation capacity. A negative RES capacity productivity effect could directly indicate decarbonisation of the electricity sector in countries where economic growth and thus electricity demand tend to be stable or grow only marginally, but the overall sources used for electricity generation are being replaced by renewable energy sources through the gradual abandonment of fossil fuels.

In most countries, population growth had a positive effect and led to an increase in electricity generated from RES, with the exception of 10 countries where the population decreased, namely Bulgaria, Greece, Croatia, Italy, Latvia, Lithuania, Hungary, Poland, Portugal, and Romania. Energy efficiency improvements have reduced energy intensity in most countries and have, therefore, had a negative impact on the amount of electricity generated from RES. However, in Belgium, Greece, and Croatia, the energy intensity of electricity generation increased during this period, contributing to a positive impact on gross electricity generation from RES. For these countries, the growth in gross electricity generation from RES between 2012 and 2021 was well above the aggregate EU growth rate for this period, while GDP growth was significantly below the average growth rate of all EU member states. This explains the overall increase in the energy intensity effect for these countries, indicating that more electricity was generally generated from RES to produce one unit of GDP. In all countries, the RES deployment per capita effect showed an increasing trend and had a positive impact on RES-generated electricity. All EU countries thus showed positive progress in the use of renewable energy per population, indicating a trend towards a green energy transition.

As for RES electricity generated from wind power, the share of wind power in the total RES energy mix has contributed positively to the total electricity generated from wind power in most countries. However, in countries such as Bulgaria, Denmark, Estonia, Spain, Cyprus, Hungary, Portugal, and Slovakia, the share of wind power in the total RES generated electricity decreased and, therefore, had a negative impact on the total gross electricity generated from wind power. Table 4 outlines the LMDI results for changes in gross electricity production from wind from 2012 to 2021.

Table 4. LMDI analysis results for changes in gross electricity production from wind, from 2012 to 2021, GWh.

	ΔWind Share Effect	**ΔRES Share Effect**	**ΔEnergy Intensity Effect**	**ΔWind Capacity Productivity Effect**	**ΔWind Deployment per Capita Effect**	**ΔPopulation Growth Effect**	**ΔGross Electricity Production from Wind**
Belgium	4432	2545	1459	−7820	8334	289	9238
Bulgaria	−560	751	−253	223	133	−80	213
Czechia	22	184	−120	−52	141	11	186
Denmark	−1962	6757	−1376	−4739	6480	625	5785
Germany	27,337	45,470	−17,139	−49,855	54,257	2897	62,967
Estonia	−193	845	−551	−1289	1484	4	299
Ireland	598	4006	−4421	−612	5508	686	5765
Greece	1620	4208	615	−6044	6424	−191	6633
Spain	−7210	23,929	−7568	−7637	10,402	674	12,589
France	13,004	9760	−2865	−20,237	21,142	850	21,653
Croatia	1158	199	121	−1445	1767	−67	1733
Italy	4023	3961	−580	−5452	5712	−144	7520
Cyprus	−185	227	−26	31	4	9	61
Latvia	31	5	−38	−4	45	−11	27
Lithuania	195	442	−140	−544	939	−69	822
Luxembourg	191	89	−80	−68	72	33	237
Hungary	−760	637	−175	193	13	−14	−106
Malta	0	0	0	0	0	0	0
Netherlands	−1062	12,674	50	−10,834	11,755	440	13,023
Austria	3997	178	−274	−3649	3712	314	4277
Poland	4732	5198	−2330	−5559	9522	−77	11,487
Portugal	−2569	4700	−301	−1364	2767	−278	2956
Romania	1536	2492	−2038	136	2100	−291	3936
Slovenia	5	1	−1	−1	2	0	6
Slovakia	−1	0	0	2	−2	0	−1
Finland	6270	1348	−17	−6716	7058	69	8012
Sweden	15,321	3349	−2116	−17,090	19,132	1483	20,080
EU-27	69,968	133,955	−40,165	−150,426	178,904	7161	199,398

The increasing share of RES in the total electricity mix has contributed positively to wind energy production in all countries. For wind energy production to increase, the total share of RES in electricity production is a strong incentive. The wind capacity productivity effect had a negative impact on the level of wind power production in almost all countries except Bulgaria, Cyprus, Hungary, and Romania. The wind deployment per capita effect was positive in all countries except Slovakia, where the per capita installation of wind power declined during the study period, suggesting that other renewable energy resources such as hydropower, solar PV and biofuels have taken a more dominant position in the overall RES mix in electricity generation.

In the EU, gross electricity generation from wind power increased by a total of 199 TWh between 2012 and 2021. The largest contributor to the increase in wind power in the EU-27 during this period was the increasing use of wind power per capita. The increasing overall share of RES in electricity generation and the effect of the wind share had a positive impact on wind energy generation. The effect of population growth also made a positive contribution, but the effect was less significant than for the other factors. The effect of wind capacity productivity and the effect of energy intensity had a negative impact on gross electricity generation from wind power.

In absolute terms, the largest increases in gross electricity generation from wind power during the study period were observed in Germany (62.97 TWh), France (21.65 TWh), and Sweden (20.08 TWh). Slovakia was the only country to record a decrease in gross electricity generation from wind power, of 1 GWh in the period from 2012 to 2021. No progress in wind energy generation was observed in Malta. Slovenia, Latvia, and Cyprus all experienced slow progress in wind-generated electricity, with an increase of 6 GWh, 27 GWh, and 61 GWh, respectively. 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 renewable energy share in electricity production, have shown proactive efforts in increasing their wind and solar PV capacities. Instead of following a similar path, 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. The results presented in this study align with the research conducted by [31], which emphasised Latvia's historical involvement in bioenergy and hydropower development. However, the country has little expertise in wind power deployment and negligible use of solar electricity. According to [31], some nations are seeing lower levels of success in the adoption and implementation of renewable energy sources, including wind energy and solar PV systems. To compensate for this, these countries are placing more emphasis on existing RES technologies, such as hydropower and biomass. However, this overemphasis on incumbent technologies might potentially hinder future RES growth.

Table 5 shows the LMDI results for the changes in gross electricity generation from solar PV over the period. Across the EU-27, an increase in gross electricity generation from PV was observed from 2012 to 2021.

Table 5. LMDI analysis results for changes in gross electricity production from solar PV, from 2012 to 2021, GWh.

	ΔSolar PV Share Effect	**ΔRES Share Effect**	**ΔEnergy Intensity Effect**	**ΔSolar PV Capacity Productivity Effect**	**ΔSolar PV Deployment per Capita Effect**	**ΔPopulation Growth Effect**	**ΔGross Electricity Production from PV**
Belgium	1053	1448	540	−2692	2973	148	3470
Bulgaria	−13	668	−238	−154	503	−78	688
Czechia	−500	733	−481	177	197	42	167
Denmark	772	360	−62	−936	1038	34	1205
Germany	6386	19,771	−6860	−19,291	21,630	1324	22,960
Estonia	309	50	−31	−338	363	1	354
Ireland	88	2	−16	−79	94	2	92
Greece	750	2132	591	−3549	3771	−139	3557
Spain	9344	4792	−1081	−12,329	12,851	152	13,729
France	8259	3382	−1093	−10,646	11,092	309	11,305
Croatia	121	6	2	−113	134	−4	147
Italy	1433	5423	−881	−6525	6840	−114	6177
Cyprus	236	184	−25	−374	414	11	447
Latvia	7	1	−1	−7	7	0	7
Lithuania	155	29	−18	−162	189	−4	189
Luxembourg	103	78	−64	−134	138	20	142
Hungary	2494	1084	−8	−2918	3153	−16	3788
Malta	19	161	−2	−181	212	31	239
Netherlands	5102	5820	−81	−10,659	10,967	155	11,305
Austria	2405	35	−94	−2347	2375	70	2445
Poland	3522	106	96	−3515	3734	−9	3933
Portugal	1488	414	−151	−2054	2162	−15	1845
Romania	1465	315	−579	−418	985	−72	1695
Slovenia	244	55	−79	−269	331	8	290
Slovakia	142	75	−88	93	20	6	247
Finland	252	28	4	−266	272	1	292
Sweden	1325	124	−27	−1406	1462	29	1507
EU-27	46,963	47,274	−10,725	−81,093	87,910	1893	92,222

The solar PV share effect contributed positively to the total gross electricity generation from solar PV in almost all countries, except in Bulgaria and the Czech Republic, where solar PV share in the total electricity mix decreased, indicating that hydropower, biofuels, and wind (in the Czech Republic) were acquiring a more dominant position in the RES mix for electricity production. The RES share effect contributed positively to gross electricity production from solar PV in all countries, indicating that an increase in the overall share of renewable energy sources had a positive impact on the overall deployment of solar PV in electricity generation.

On the other hand, the solar PV capacity productivity effect had a negative impact on electricity generation from solar PV in all countries except the Czech Republic and Slovakia.

This is explained by the fact that in the Czech Republic and Slovakia, over the period from 2012 to 2021, only modest increases in solar PV installed capacities below the EU average growth rate were observed. Negative impacts on the overall changes in gross electricity generation from PV were also due to the energy intensity effect, except in Belgium, Greece, Croatia, Poland, and Finland, which can be explained by the fact that these countries demonstrated the greatest increases in installed solar PV capacities between 2012 and 2021. Solar PV deployment per capita increased in all EU-27 countries and contributed positively to gross electricity production from solar PV.

In absolute terms, Germany (22.9 TWh), Spain (13.7 TWh), France (11.3 TWh), and the Netherlands (11.3 TWh) achieved the largest growth in gross electricity generation from solar PV between 2012 and 2021. In contrast, Latvia (6.8 GWh) and Ireland (92.3 GWh) recorded the slowest progress.

In the EU-27, total gross electricity generation from solar PV increased by 92 TWh. The largest contributors to the changes in electricity generated by PV were the increase in per capita use of PV, the solar PV share effect, and the RES share effect. Population growth also made a positive contribution, while PV capacity productivity and the energy intensity effect had a negative impact on the changes in gross electricity generation from solar PV.

4.3. Differences between the Four Main Regional Groups

The results of the LMDI decomposition analysis were further analysed based on their division into regional groups in order to determine the principal differences and similarities between regions. The countries in this paper were divided into four main regional groups—Northern Europe, Central Western Europe, Central Eastern Europe, and Southern Europe [58]. Figure 4 and Table 6 provide an overview of the countries included in each group.

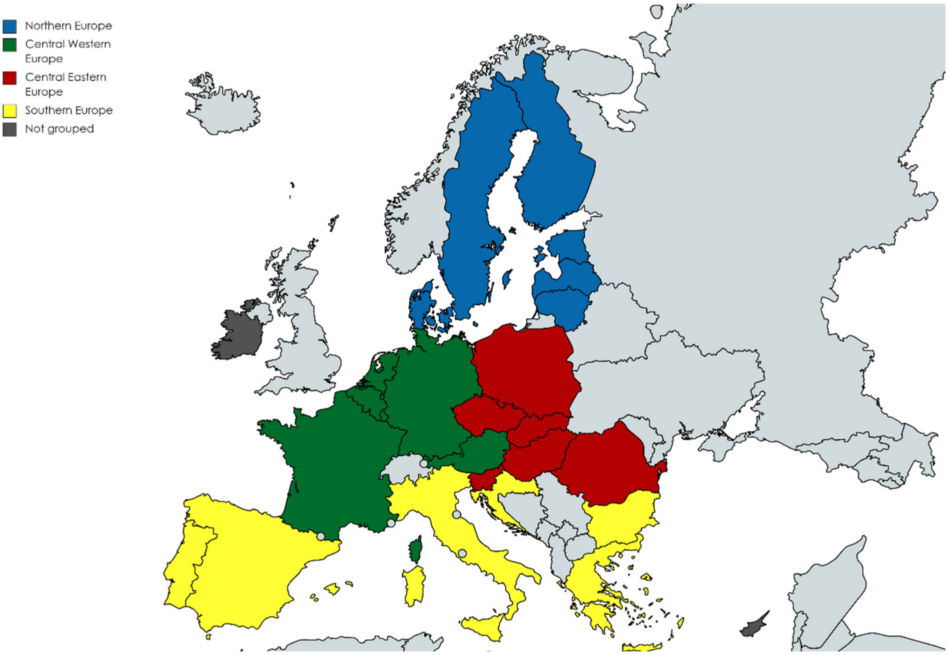

Figure 4. Division of EU-27 into country groups according to regional electricity wholesale markets.

Table 6. Regional electricity markets in the EU, adapted from [58].

Region	**EU Countries Included**
Northern Europe	Sweden, Finland, Denmark, Estonia, Latvia, and Lithuania
Central Western Europe	Germany, France, Belgium, Austria, the Netherlands, and Luxembourg
Central Eastern Europe	Poland, the Czech Republic, Slovakia, Slovenia, Hungary, and Romania
Southern Europe *	Bulgaria, Croatia, and Greece, Italy and Malta, Spain, and Portugal

* Aggregated results for South-Eastern Europe, Apennine Peninsula, Iberian Peninsula regions.

The division into categories was based on the classification of regional electricity wholesale markets by the European Commission [58]. Southern Europe includes the regions of South-Eastern Europe (Bulgaria, Croatia, and Greece), Apennine Peninsula (Italy and Malta), and Iberian Peninsula (Spain and Portugal). Ireland and Cyprus were excluded from the grouping division due to their lack of alignment with the predetermined criteria for grouping. Originally, Ireland was grouped together with the UK to form the British Isles regional wholesale electricity market. However, in this study, only EU countries were included in the classification of the respective groups.

Figure 5 and Table 7 depict LMDI results for changes in gross electricity production from RES for each of the four regions and the EU-27. The impact of population growth was shown to be positive in Northern Europe and Central Western Europe, whereas it exhibited a negative influence in Central Eastern Europe and Southern Europe.

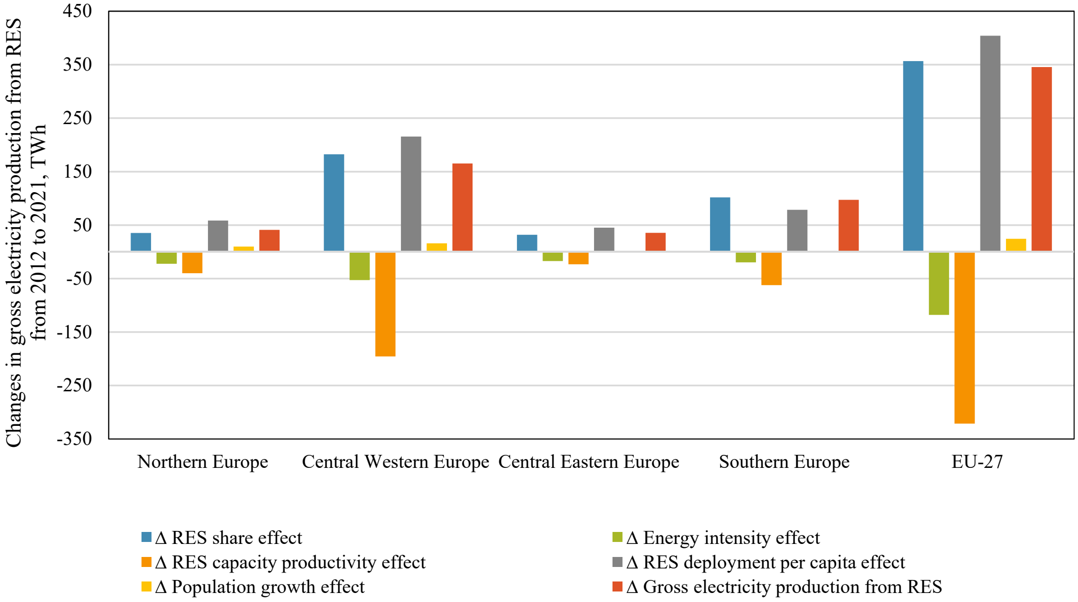

Figure 5. Comparison between LMDI regional electricity market aggregate results.

The primary factor driving the total growth in gross electricity production from renewable energy sources in Northern Europe, Central Western Europe, and Central Eastern Europe was the RES deployment per capita effect. However, the primary influential element in Southern Europe was the RES share effect. The second primary factor that influenced the changes in the amount of electricity produced from RES in Northern Europe and Central Western Europe was the negative effect on RES capacity productivity.

Table 7. LMDI results for changes in gross electricity generation from RES in EU regional electricity markets during 2012–2021, GWh.

	Northern Europe	Central Western Europe	Central Eastern Europe	Southern Europe	EU-27
ΔRES share effect	35,203	182,365	31,794	101,809	356,645
ΔEnergy intensity effect	−22,518	−52,875	−17,316	−19,756	−117,979
ΔRES capacity productivity effect	−40,006	−195,634	−23,314	−62,274	−321,478
ΔRES deployment per capita effect	58,441	215,524	45,181	78,513	404,033
ΔPopulation growth effect	9742	15,869	−969	−1183	24,323
ΔGross electricity production from RES	40,862	165,249	35,376	97,108	345,544

Figures 6–10 show the annual changes in gross electricity generation from RES for all regional country groups.

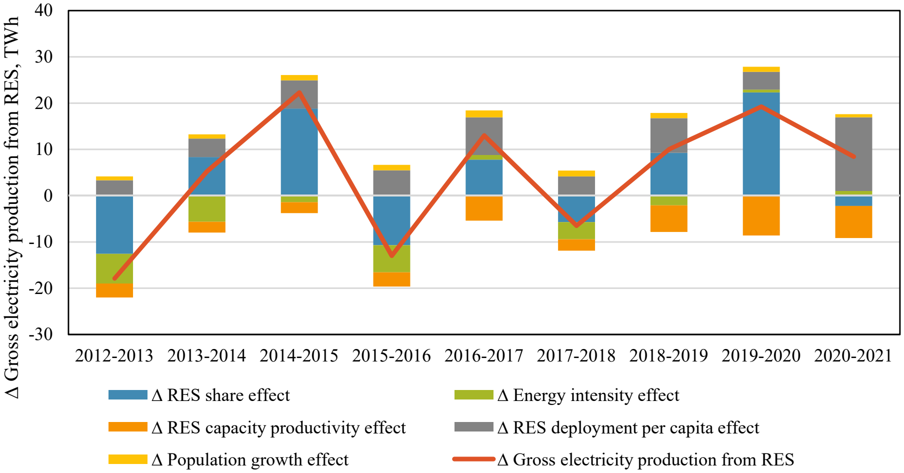

Figure 6. LMDI decomposition analysis results for annual changes in gross electricity generation from RES in Northern Europe.

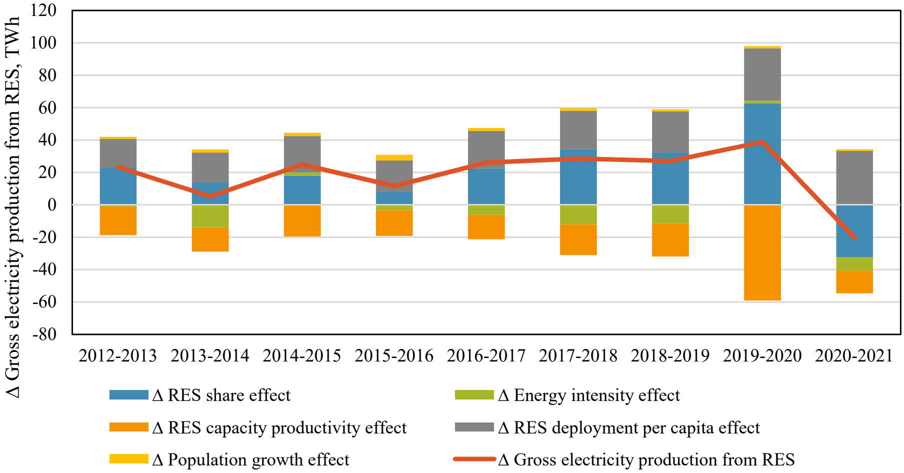

Figure 7. LMDI decomposition analysis results for annual changes in gross electricity generation from RES in Central Western Europe.

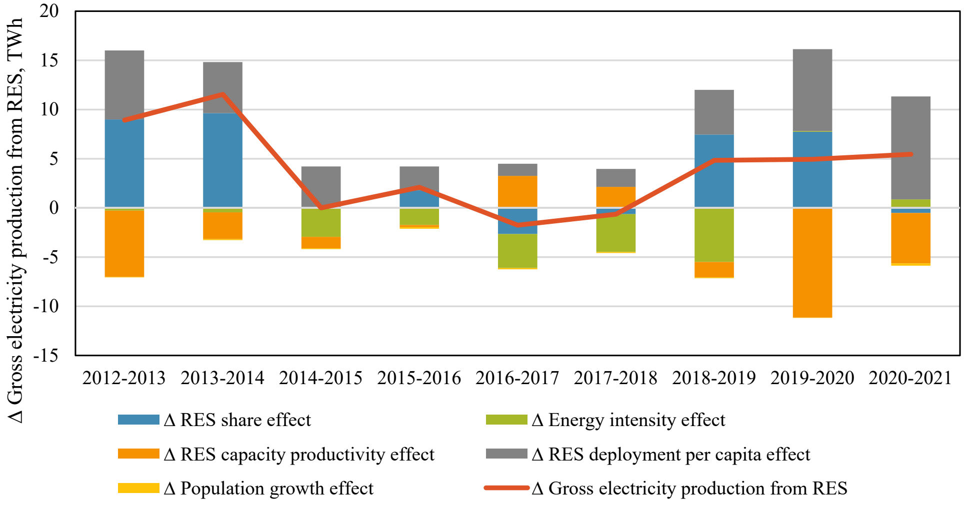

Figure 8. LMDI decomposition analysis results for annual changes in gross electricity generation from RES in Central Eastern Europe.

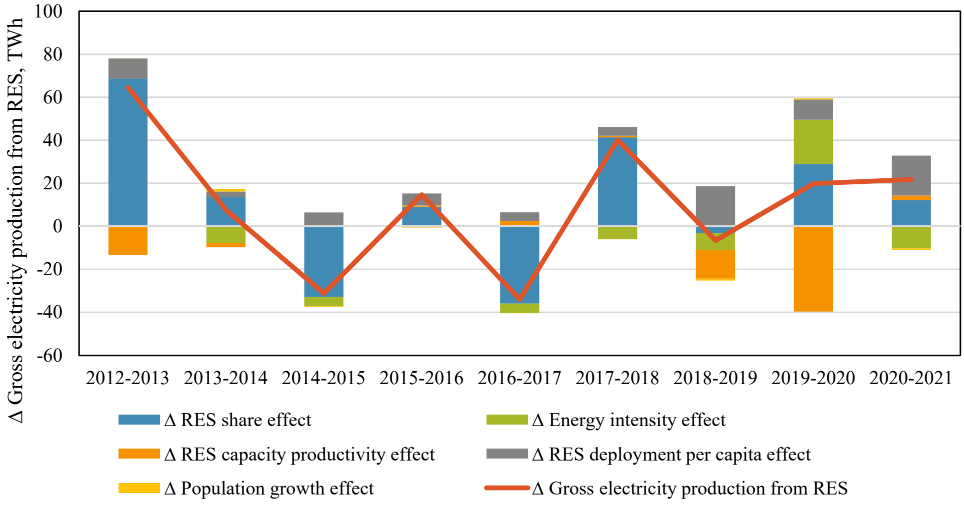

Figure 9. LMDI decomposition analysis results for annual changes in gross electricity generation from RES in Southern Europe.

In Northern Europe, there were significant fluctuations in gross electricity production from renewable energy sources during the study period. These fluctuations can be attributed, in part, to the substantial contribution of hydropower in the total RES electricity mix. In fact, hydropower constituted a significant 50% of the total RES electricity generation in this region. The findings indicate that there was a rise in energy intensity during the timeframe spanning from 2019 to 2021. Notably, the results suggest that energy efficiency improvements did not have a major impact on this observed trend. Northern Europe has seen consistent and stable population growth, which has had a positive effect on the amount of electricity produced from RES. This growth can be largely attributed to the increasing population in Scandinavian countries, even though the Baltic states have experienced a decrease in their populations.

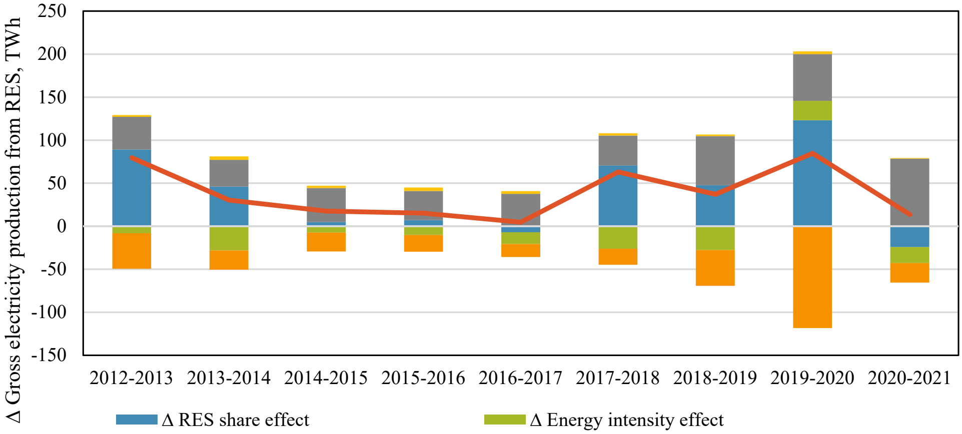

Figure 10. LMDI decomposition analysis results for annual changes in gross electricity generation from RES in EU-27.

Central Western Europe has shown consistent and stable growth in gross electricity production from renewable energy sources, except for a decrease observed during the period from 2020 to 2021. In this region, wind energy plays a significant role, constituting 40% of the total electricity production from renewable sources, which is the largest share compared to other regional groups. This high share of wind energy could explain the smaller fluctuations and the more rapid and constant growth in renewable energy production compared to Northern Europe. Moreover, Central Western Europe has experienced steady but modest population growth, which has had a positive impact on the gross electricity production from renewable sources. Although the overall energy intensity effect was pushing down the amount of renewable energy produced during the study period, there was a positive effect noted in the period from 2019 to 2020. A study conducted by [45] posits that despite a huge increase in the overall installed capacities of renewable energy in Western Europe, there has been no significant improvement in the overall energy efficiency of electricity generation [45].

Central Eastern Europe exhibited notable growth in gross electricity generation from renewable energy sources between 2012 and 2016. However, this growth slowed down and experienced a downturn during the period from 2014 to 2018, only to pick up again from 2018 to 2021. During the past two periods, from 2019 to 2021, the energy intensity effect had a positive impact, indicating that energy efficiency improvements in electricity generation were not effective. The results also revealed a fluctuating RES capacity productivity effect, which means that the productivity of renewable energy sources varied over time. Additionally, there was a minimal negative population growth effect observed during the same period. In terms of the energy mix, Central Eastern Europe has similar shares for hydro energy and wind energy. However, a high share of biofuels helps to compensate for fluctuations in electricity generation driven by hydropower.

In Southern Europe, both hydro and wind energy sources contribute nearly equally to the electricity mix, while solar energy holds the highest share compared to other regions. However, the total gross electricity generation from RES in Southern Europe shows significant fluctuations. The two most substantial drops in gross electricity generation from RES occurred during the periods of 2014–2015 and 2016–2017, both of which were driven by a negative RES share effect. The energy intensity effect was positive during

2019–2020, suggesting that there might not have been sufficient progress in improving energy efficiency during that period.

The aggregated results for the EU-27 indicate a consistent and continuous growth in gross electricity generation from RES. Consistent reductions in energy intensity had a significant negative impact on the quantity of electricity produced from RES in the EU-27, according to the findings. These results align with the findings of [45], who discovered that the energy intensity effect is a significant negative contributor to the quantity of RES electricity generated [45]. However, there was a concerning trend revealed by the positive energy intensity in 2019–2020, suggesting that there might not have been sufficient progress in improving energy efficiency in electricity generation across the EU-27.

Tables 8 and 9 depict LMDI results for the changes in gross electricity generation from wind and solar PV, respectively, in the EU regional electricity markets over the period 2012–2021. The findings reveal that the deployment of wind and solar PV per capita effect had the most significant influence on changes in gross electricity generation from these sources across all regional country groups, except for Southern Europe.

Table 8. LMDI results for changes in gross electricity generation from wind in EU regional electricity markets during 2012–2021, GWh.

	Northern Europe	Central Western Europe	Central Eastern Europe	Southern Europe	EU-27
ΔWind share effect	19,662	47,898	5534	−3540	69,968
ΔRES share effect	12,746	70,715	8512	37,748	133,955
ΔEnergy intensity effect	−4238	−18,848	−4665	−7967	−40,165
ΔWind capacity productivity effect	−30,383	−92,463	−5281	−21,718	−150,426
ΔWind deployment per capita effect	35,137	99,272	11,778	27,205	178,904
ΔPopulation growth effect	2101	4821	−371	−86	7161
ΔGross electricity production from wind	35,025	111,395	15,507	31,644	199,398

Table 9. LMDI results for changes in gross electricity generation from solar PV in EU regional electricity markets during 2012–2021, GWh.

	Northern Europe	Central Western Europe	Central Eastern Europe	Southern Europe	EU-27
ΔSolar PV share effect	2820	23,309	7367	13,143	46,963
ΔRES share effect	592	30,535	2367	13,595	47,274
ΔEnergy intensity effect	−135	−7651	−1139	−1759	−10,725
ΔSolar PV capacity productivity effect	−3116	−45,769	−6851	−24,904	−81,093
ΔSolar PV deployment per capita effect	3332	49,176	8420	26,474	87,910
ΔPopulation growth effect	61	2027	−42	−166	1893
ΔGross electricity production from solar PV	3553	51,626	10,121	26,382	92,222

Moreover, the impact of the RES share effect was more pronounced in wind-generated electricity compared to LMDI results for solar PV. This suggests that increasing the overall share of renewable energy sources has a stronger effect on the amount of electricity generated from wind. This could be attributed to the fact that wind energy has larger capacity and production capabilities for electricity compared to solar PV.

The comparison of regional groups showed a notable contrast in Southern Europe. While the wind share effect was negative, indicating a decrease in the share of wind energy in the total RES mix for electricity production over the study period, the overall RES share remained positive and dominant in this region. However, what stands out is the swift rise in the solar PV share, which is growing at a faster pace and surpassing wind energy in Southern Europe. This suggests that solar photovoltaic installations are gaining more prominence and becoming the dominant source of renewable energy in the Southern European region.

When compared to other regional country groups, it is evident that the energy intensity effect is somewhat weaker in Northern Europe. This suggests that the implementation of energy efficiency measures in power generation has not resulted in any substantial influence.

The results reveal that in Central Eastern Europe, wind capacity and solar PV capacity productivity effects were notably weaker when compared to the Central Western Europe regional country group. This indicates that capacity productivity experienced a more substantial decrease in Western countries.

The results are consistent with the findings of [39], which decomposed changes in energy-related CO_2 emissions in EU countries by comparing four different groups of countries: The Northern European group (Finland, Denmark, Ireland, United Kingdom, and Sweden); the Southern European group (Italy, Spain, Greece, Slovenia, and Portugal); the Western European group (France, Netherlands, Belgium, Austria, Germany, and Luxembourg); and the Central Eastern European group (Poland, Czech Republic, Hungary, Slovakia, and Estonia). The results of the LMDI analysis showed a negative effect on renewable capacity productivity in Western European countries and a positive effect in Central and Eastern European countries [39].

These findings also align with the study conducted by [37], which revealed a negative resource productivity effect for European countries including Belgium, Denmark, Austria, and Norway for the time period from 1985 until 2011. The study argued that this negative trend could be attributed to the fact that more-developed countries are generally more inclined to invest in renewable energy capacities [37].

5. Conclusions

This study applied the logarithmic mean Divisia index (LMDI) decomposition analysis to examine the primary factors influencing the changes in electricity generated from renewable energy sources in the EU-27 during the decade from 2012 to 2021. The research determined five key factors and thoroughly investigated their respective contributions to the changes in gross electricity production from RES: the RES share effect, energy intensity effect, RES capacity productivity effect, RES deployment per capita effect, and population growth effect.

The aggregated results for the EU-27 countries showed that the main factors contributing positively to the total gross electricity generation from RES were the RES deployment per capita effect and the RES share effect, while the RES capacity productivity effect and energy intensity effect contributed negatively. The population growth effect also contributed positively to the amount of RES-generated electricity, but the effect was not as significant as for the other factors.

In the EU, total gross electricity generation from RES increased by 45.7% during the period from 2012 to 2021. In total, 16 countries reported a change in gross electricity generation from RES above the EU level during this period. The cross-country comparison showed that countries with lower levels of RES diversification may be exposed to greater fluctuations in renewable energy production volumes. Moreover, some countries that have already achieved a high share of RES in their electricity generation (e.g., Latvia, Sweden, Austria) have made slower progress in the deployment of RES over the last decade. Certain countries are encountering challenges in effectively embracing and putting into practice emerging renewable energy sources (RES), notably wind energy and solar photovoltaic (PV) systems. In response, these nations are prioritizing the utilization of well-established RES technologies like hydropower and biomass. However, this heightened focus on established technologies could potentially impede the future advancement of RES.

The study also separately examined the main drivers of change in wind and solar PV electricity generation, driven by six main factors: the wind/solar PV share effect, RES share effect, energy intensity effect, wind/solar PV capacity productivity effect, wind/solar PV deployment per capita effect, and population growth effect.

Between 2012 and 2021, gross electricity generation from wind power in the EU saw a substantial increase, of 199 TWh. The primary driver for this growth was the wind deployment per capita effect. The overall share of RES in electricity generation, the wind share effect, and the population growth effect had a positive impact on wind energy generation, while the wind capacity productivity and energy intensity effects had negative contributions. In absolute terms, the largest increases in gross electricity generation from wind power during the study period were observed in Germany (62.97 TWh), France (21.65 TWh), and Sweden (20.08 TWh).

Similar findings were also observed in the LMDI results for solar PV-generated power. In the EU-27, total gross electricity generation from solar PV increased by 92 TWh. The largest contributors to the changes in electricity generated by solar PV were the solar PV deployment per capita effect, solar PV share effect, and RES share effect, followed by a minor population growth effect. PV capacity productivity and the energy intensity effect negatively impacted the changes in gross electricity generation from solar PV. In absolute terms, Germany (22.9 TWh), Spain (13.7 TWh), France (11.3 TWh), and the Netherlands (11.3 TWh) achieved the largest growth in gross electricity generation from solar PV between 2012 and 2021.

The LMDI results indicated that the impact of the RES share effect was more noticeable in wind-generated electricity when compared to the LMDI results for solar PV. This phenomenon may be attributed to the fact that wind energy exhibits greater capacity and production capabilities in generating electricity in comparison to solar PV systems. This implies that boosting the overall share of RES has a more substantial impact on the amount of electricity generated from wind. In general, the aggregated results for the EU-27 countries showed that an increasing overall share of renewable energy resources positively influences the overall deployment of wind and solar energy in electricity generation.

The deployment of RES per capita effect was the main driver of the total growth in gross electricity production from RES in Northern Europe, Central Western Europe, and Central Eastern Europe, according to comparisons between regional groups. The RES share effect, however, was the main driving force in Southern Europe. The decrease in RES capacity productivity was the second major factor that affected variations in the quantity of energy generated by RES in Northern Europe and Central Western Europe.

A significant divergence in Southern Europe was shown when regional groupings were compared. The overall RES share in this region remained positive and predominant, despite the fact that the wind share impact in Southern Europe was negative, showing a decline in the percentage of wind energy in the entire RES mix for electricity generation throughout the research period. The rapid growth in the solar PV share is outpacing wind energy in Southern Europe. This could be explained by the fact that countries in Southern Europe, such as Spain, Italy, and Greece, have a significant advantage in terms of solar irradiation and, consequently, an abundance of solar resources. These regions receive ample sunlight throughout the year, making solar photovoltaic installations highly productive and efficient.

The findings show that compared to the Central Western Europe regional group, the impact of wind capacity and solar PV capacity productivity was much smaller in Central Eastern Europe. This revealed that capacity productivity fell more precipitously in Western countries, showing that more-developed countries are often more likely to invest in renewable energy facilities. The overall LMDI findings revealed that there is a need for further investments and efforts to fully integrate renewable energy sources and advance sustainable development since economic growth in poorer countries is outpacing increases in their renewable energy capacity.

Further research should investigate the effects of changes in renewable energy capacity productivity on renewable electricity generation in greater depth. This study's country scenarios demonstrated that a growth rate in electricity capacities from RES that surpasses GDP growth results in a decline in electricity generation from RES, which might seem counterintuitive. Using, for instance, econometric models and larger time series historical data, future research could focus on the economic growth aspect and its effect on the amount of renewable electricity generation. In addition, more in-depth research on the optimal level of economic growth is required to support the development of a sustainable renewable electricity generation infrastructure as global energy demand increases alongside GDP. If the aggregate demand for electricity decreases as a result of slower economic growth, it is not necessary to produce as much electricity. Moreover, as similarly discovered in a study by [59], with weaker or declining economic growth, the economy generates fewer investments that can be attributed to the development of renewable energy generation infrastructure, as the quantity of investments is dependent on economic growth.

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PAPER 6: HOW INDEPENDENT IS THE ENERGY SECTOR IN THE EU?

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How Independent is the Energy Sector in the EU?

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ABSTRACT

The current geopolitical situation and the Russian invasion in Ukraine have urgently increased the role of energy independence in national energy security. Nevertheless, the European Union, is still very dependent on imports of fossil fuels such as oil and natural gas, which are mainly sourced from neighboring Russia. Now more than ever, to accelerate Europe's energy independence and transition to carbon neutrality, it is critical to restructure national energy infrastructures and promote the rapid development of local renewable energy resources. To understand whether the EU are ready to accelerate the decarbonization of their energy system by abandoning energy imports from Russia, it is necessary to assess what progress has been made so far in reducing net energy imports. In this study, Log-Mean Divisia Index (LMDI) decomposition analysis is used to examine the changes in net energy imports in the EU-27 during the period from 1995 to 2020. The change in net energy imports is measured by four main factors: changes in energy dependence, changes in energy intensity, changes in economic growth, and population. The results show that not only has no progress been made in reducing the EU's energy import dependency, but the situation has actually worsened and become more unstable over the past five years.

Keywords: energy independence; LMDI; decomposition analysis; net energy imports

NONMENCLATURE

Symbols	
NI	Net energy imports
EN	Gross available energy
GDP	Gross domestic product
POP	Population
DEP	Energy import dependency
EE	Energy efficiency
EC	Economic growth

1. INTRODUCTION

Current geopolitical situation shows that energy is no longer perceived as just a necessary commodity but as an asset that can be weaponized. In light of the changing political environment and the increasing impact of climate change, energy security is becoming an essential component of a country's economic, environmental, and social stability [1]. Following the Russian invasion of Ukraine, the EU expressed concern about increasing the EU's energy independence and therefore launched REPowerEU in May 2020: Joint European Action for More Affordable, Secure and Sustainable Energy. It is a plan to increase Europe's energy independence and end fossil energy imports from Russia before 2030. This plan aims to promote the implementation of energy efficiency measures, diversify current energy suppliers, and accelerate the use of RES by exploiting the maximum potential of local RES to compensate for Russian energy imports and support Europe's energy independence [2].

Energy independence becomes an important driver and predictor of a country's economic development, as energy is used in all major sectors of the economy and energy costs impact all the main supply chains of the economy [3]. Energy security is also addressed in the United Nations Sustainable Development Goals, where net energy import dependency is used as an indicator of countries' level of national energy security [4]. Energy import dependency is also one of the main parameters that is used to explain the overall energy system infrastructure of the country [5]. Increasing energy import dependency means that the energy system is more dependent on external resources than on its own, making it more vulnerable to geopolitical threats that can cause significant disruptions to energy supplies [6].

Literature shows that there are studies that examine the degree of energy independence in each country, but there are fewer articles that look at progress in reducing national energy imports and increasing energy self-sufficiency. Moreover, there is no generally accepted method for studying changes in the level of energy security and net energy imports. A study by [7] uses decomposition analysis to show how energy efficiency improvements positively affect energy independence. However, another study by [8] evaluates the impact of renewable energy development on regional energy independence using the GIS method. A study by [9] uses econometric methods to show the role of interdependencies among countries in providing energy imports to ensure uninterrupted energy supply and their implications for future energy security.

This study applies Log-Mean Divisia index (LMDI) decomposition analysis to examine the changes in net energy imports in the EU-27 during the period from 1995 to 2020. The analysis allows to identify the main drivers of change in net energy imports and to understand what progress has been made in reducing the EU's energy import dependency. Assessing progress is important for policymakers to avoid making expensive mistakes and develop more effective sustainability strategies for the future based on historical experience [10].

2. METHODOLOGY

Index decomposition analysis (IDA) is a comprehensive mechanism that allows to identify the main drivers of change in environmental performance indicators [11]. The conceptual framework of IDA is based on the decomposition of the study phenomenon, breaking down the element of the research study into several factors to examine their influence on the outcome [12]. Two main IDA frameworks can be distinguished - the Divisia index decomposition and the Laspeyres index decomposition. The difference between the two methods lies in the residuals obtained during the decomposition, where the Laspeyres index produces residual terms, while the Divisia index produces a perfect decomposition with no residuals [13]. This study applies Divisia index method due to its advantageous property of perfect decomposition. Furthermore, Divisia index method can take two forms – arithmetic mean or logarithmic mean, as well as integrate two main calculation approaches - additive or multiplicative [14]. This study uses logarithmic mean Divisia index (LMDI) with additive approach in order to study changes in absolute values of net energy imports. LMDI method is one of the most frequently used IDA methods to study energy efficiency [15], [16], sustainability [17], greenhouse gas emissions [18], and other green transformation challenges.

This study applies the LMDI decomposition analysis method to study changes in net energy imports of European Union countries. According to LMDI, changes in net energy imports are 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. (1). Net energy imports are expressed as energy imports minus energy exports. Table 1 summarizes all the factors used in the decomposition analysis.

$$NI = \sum_i NI_i = \sum_i \frac{NI}{EN}\frac{EN}{GDP}\frac{GDP}{POP}POP = \sum_i DEP_i\, EE_i EC_i POP_i \quad (1)$$

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

Table 1
Description of LMDI decomposition analysis factors

Factor	Indicator	Description
Energy dependency effect (*DEP*)	Net imports (imports-exports) per gross available energy (NI_i/EN_i)	Measures changes in energy import dependency and reliance on energy resources abroad. Positive value shows greater energy import dependency and negative value shows reduced energy import dependency.
Energy efficiency effect (*EE*)	Gross available energy per gross domestic product (EN_i/GDP_i)	Measures improvements in energy efficiency by reduced energy intensity of economy. Positive value shows negative trend and decrease in energy efficiency, negative value shows significant improvements in energy efficiency by more efficient use of energy resources.
Economic growth effect (*EC*)	Total gross domestic product per number of inhabitants (GDP_i/POP_i)	Measures changes in economic growth and development which directly impact the amount of energy resources used in the economy. Positive value shows increase in economic growth and its impact on energy demand increase, negative value shows decrease in economic output which in turn decreases overall demand for energy.
Population growth effect (*POP*)	Total number of inhabitants (POP_i)	Measures changes in total number of inhabitants in a country. Positive value shows growth in population which pushed energy demand to increase, negative value shows decline in population which requires less energy resources to meet the needs of inhabitants.

Furthermore, the equation is derived in Eq. (2) that measures changes in net energy imports from future year *T* to initial year *0*.

$$\Delta NI = NI^T - NI^0 = \Delta NI_{DEP} + \Delta NI_{EE} + \Delta NI_{EC} + \Delta NI_{POP} \quad (2)$$

Changes in each decomposition factor from Eq. (2) is calculated according to Eq. (3)-(6):

$$\Delta\ NI_{DEP} = \sum_i \frac{NI^T - NI^0}{lnNI^T - lnNI^0} ln \frac{DEP_1^T}{DEP_1^0} \quad (3)$$

$$\Delta\ NI_{EE} = \sum_i \frac{NI^T - NI^0}{lnNI^T - lnNI^0} ln \frac{EE_1^T}{EE_1^0} \quad (4)$$

$$\Delta\ NI_{EC} = \sum_i \frac{NI^T - NI^0}{lnNI^T - lnNI^0} ln \frac{EC_1^T}{EC_1^0} \quad (5)$$

$$\Delta\ NI_{POP} = \sum_i \frac{NI^T - NI^0}{lnNI^T - lnNI^0} ln \frac{POP_1^T}{POP_1^0} \quad (6)$$

where NI^T is net energy imports in the future year; NI^0 is net energy imports in the initial year.

All the data used for this study is collected from the Eurostat database. Data on net energy imports and gross available energy are collected from complete energy balances [nrg_bal_c] data set. Data on gross domestic product is collected from GDP and main components [nama_10_gdp]data set. Data on number of inhabitants are collected from population on 1 January [demo_pjan] data set. Data set on energy import dependency [sdg_07_50] and share of renewable energy in gross final energy consumption by sector [sdg_07_40] was used to validate the results obtained in the LMDI decomposition analysis of this study. Data were collected for all 27 EU member states for the period from 1995 to 2020 which was the latest available year for all the selected LMDI indicators [19]–[23].

3. RESULTS

The LMDI decomposition analysis is applied to measure the changes in net energy imports in EU-27 over the period from 1995 to 2020 divided into five groups of five-year periods. More detailed analysis is performed for the period of the last five years (2015-2020) for all 27 EU countries to examine the recent situation in accelerating energy independence at the EU level. The results show different energy structures and energy import tendencies for the countries.

Figure 1 illustrates the results of the LMDI decomposition analysis for the EU-27 for the period 1995 to 2020. The results show that economic growth and population growth are the main drivers of total energy demand growth, which in turn increases the need for net energy imports in the EU. The EU's energy import dependency has fluctuated over the periods. In the first two periods (1995-2000 and 2000-2005), there was an upward trend in energy import dependence, which was reflected in annual increases and greater EU exposure to energy trade. In the third period (2005-2010), the EU's overall energy import dependency showed slightly, decreasing trend which was mainly due to the global financial crisis, which reduced energy demand in all EU countries. In the fourth period (2010 - 2015), the EU's dependence on energy imports increased only minimally compared to growth in 1995-2005 due to implemented climate action plans, which put pressure on EU countries to increase the share of renewable energy in total energy consumption.

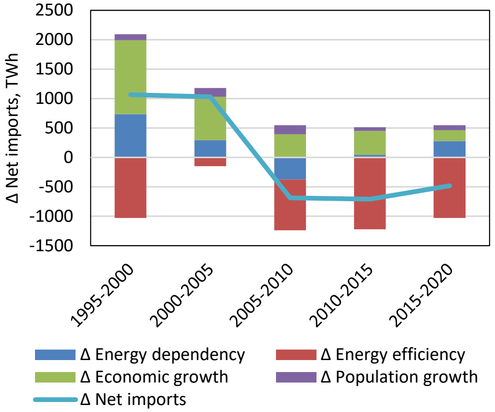

Fig. 1 LMDI decomposition analysis results for EU-27

In the fifth, the most recent period (2015-2020), the EU show rising energy import dependency that have reached the highest value compared to other periods. The growing dependence on energy imports is explained by the stable energy demand in the EU, where the growing economy and population demand fossil fuels, which are mainly consumed in transport, industry, households and agriculture. However, due to the EU's strategic climate change policies, the EU has significantly reduced its domestically generated fossil energy during 2015-2020. Therefore, to balance the energy demand, the required fossil energy was imported from abroad, mainly from Russia [24]. This has in turn pushed net energy imports during 2015-2020 to increase.

The importance of energy efficiency measures is also highlighted in the results of the LMDI decomposition analysis, as energy efficiency was the most important counter-response factor that decreased the need for net energy imports in all periods studied. The greatest impact of energy efficiency improvements was in the period from 2010 to 2015.

Figure 2 illustrates the contribution of the LMDI decomposition analysis factors to the changes in EU-27 net energy imports for the fifth study period (2015-2010), as well as the percentage change in total net energy imports over this period. Moreover, Table 2 summarizes the results for each country.

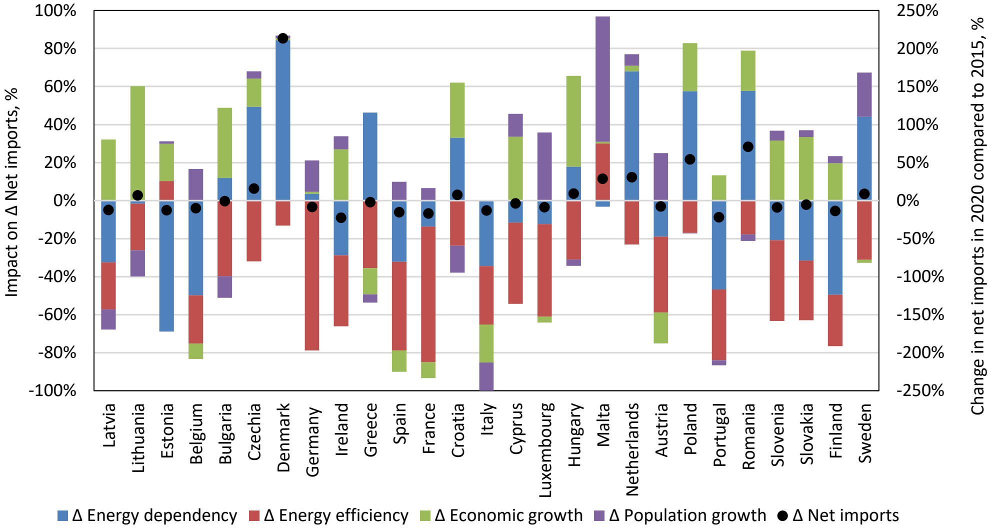

Fig. 2 Contribution of LMDI decomposition analysis factors to ΔNet imports for EU-27 in the period from 2015 to 2010

Table 2
LMDI decomposition analysis results from 2015 to 2020 for EU-27 (GWh)

Country code	Δ Energy dependency	Δ Energy efficiency	Δ Economic growth	Δ Population growth	Δ Net imports
LV	-3118	-2364	3083	-1021	-12.4%
LT	-361	-5281	12969	-2954	6.9%
EE	-1528	227	435	29	-12.5%
BE	-42974	-21831	-7039	14352	-9.9%
BG	3039	-10179	9478	-2927	-0.7%
CZ	34172	-22102	10179	2722	15.9%
DK	66920	-10445	786	1138	213.3%
DE	11952	-268706	3621	56584	-8.5%
IE	-30082	-39021	28206	7211	-22.7%
EL	29602	-22685	-8873	-2792	-2.2%
ES	-68306	-98778	-24019	20981	-15.4%
FR	-37083	-194658	-22623	17988	-16.9%
HR	4944	-3555	4358	-2126	7.5%
IT	-62686	-55787	-36252	-26973	-12.9%
CY	-1379	-5130	4015	1451	-3.6%
LU	-1749	-6908	-435	5088	-8.6%
HU	8183	-14197	21899	-1560	9.1%
MT	-252	2392	81	5253	28.8%
NL	196205	-66484	8525	17231	30.6%
AT	-6903	-14540	-5926	9094	-7.7%
PL	157877	-46741	69516	-502	54.0%
PT	-30285	-24141	8663	-1696	-22.1%
RO	43875	-13515	16048	-2565	70.8%
SI	-2615	-5338	3979	634	-8.9%
SK	-7254	-7196	7668	836	-5.2%
FI	-23580	-12829	9388	1739	-13.8%
SE	19555	-13858	-682	10370	9.0%
EU-27	**256172**	**-983649**	**117047**	**127589**	**-5.0%**

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.

In absolute terms, the countries with the highest net energy imports are Germany, Italy, France, Spain, the Netherlands, Poland, and Belgium, so changes in energy import dependency in these countries strongly influence the overall degree of energy independence of the EU.

The supply of natural gas and petroleum products is the main cornerstone for strengthening energy independence in almost all countries of the European Union [1]. 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 [25], [26]. 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 [27].

A study by [28] estimates that it is possible to reduce dependence on imported natural gas by implementing energy efficiency measures, especially in the non-profit consumer and heat generation sectors. More importantly, increasing energy self-sufficiency can be achieved not only through energy efficiency measures, but also by building the necessary infrastructure and enabling environment for domestic energy production. In addition, the study shows empirical results that demonstrate historical periods in which a reduction in natural gas consumption was achieved despite increasing economic growth [28]. Therefore, more serious measures should be taken in all EU member states to phase out natural gas use in all sectors of the economy.

Energy independence can be accelerated by increasing the use of renewable energy (RES), which enables the generation of clean energy based on local resources, even in countries without available conventional energy sources [29]. Therefore, the development of sufficient infrastructure to exploit the maximum potential of renewable energy, which includes RES production, distribution and accumulation technologies, is extremely important for all EU countries [29]. RES contributes to the EU's two main strategic development priorities. First, RES is the key element for the decarbonization of the energy system and contributes to the achievement of climate change mitigation goals. Second, it strengthens national energy security by making it possible to become less dependent on external energy resources sourced through massive energy imports [29]. The greatest advantage of RES is that it is not limited to one energy carrier that is a depleting resource, but offers a wide variety of energy sources such as wind, solar, biomass, geothermal, and hydro. Therefore, depending on the geographical and climatic conditions, it is possible for each country to develop RES infrastructure for the higher production of a specific type of RES [29]**.**

In order to show the positions of each EU-27 country in terms of level of energy import dependency and the share of renewable energy sources in total energy consumption, a correlation analysis is performed. Figure 3 illustrates the relationship between the share of renewables in gross final energy consumption and energy import dependency in 2020 for all 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.

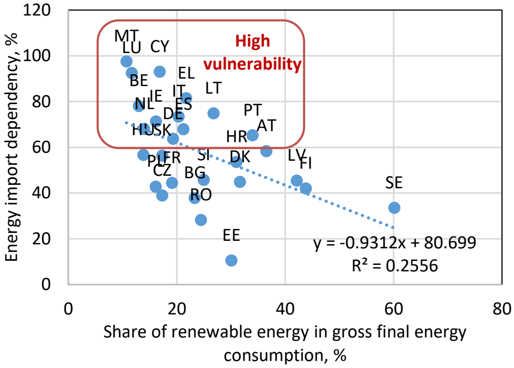

Fig. 3 Relationship between share of renewable energy in gross final energy consumption and energy import dependency in 2020 for EU-27 countries

4. CONCLUSIONS

Although EU energy import dependency was raised as an important issue back in 2015, when negotiations on the EU Energy and Climate Strategy 2030 began in response to Russia's escalating aggression in Ukraine [30], the results of this study reveal alarming findings. Not only has no progress been made in reducing the EU's dependence on imported energy, but the situation has actually worsened and become more unstable over the past five years.

The results show that at the EU level in the past five years (2015-2020) energy import dependency have increased significantly. Current improvements in energy efficiency have not been able to compensate for energy demand influenced by population and economic growth in the EU. Growth in net energy imports and import dependency is explained by the reduction in domestically generated fossil energy in EU-27 which was driven by stringent climate action plans [24]. Therefore, to compensate the demand, the necessary fossil fuels were imported. The EU has relied not only on oil imports, but also on natural gas, as natural gas is still considered a transitional source on the road to carbon neutrality [31]. In most countries, there is still lack of serious action towards more rapid replacement of natural gas in energy systems.

The results of this study suggest that, in addition to energy efficiency measures, a rapid switch to local renewable energy sources is key to phasing out imported fossil fuels, strengthening national energy security, and promoting the EU's transition to climate neutrality [32], [33]. In addition, accumulation technologies that compensate for the disruption of variable energy play a crucial role in the more rapid deployment of renewable energy resources [34].

ACKNOWLEDGEMENT

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PAPER 7: REALIZING RENEWABLE ENERGY STORAGE POTENTIAL IN MUNICIPALITIES: IDENTIFYING THE FACTORS THAT MATTER.

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Realizing Renewable Energy Storage Potential in Municipalities: Identifying the Factors that Matter

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***Abstract* – The share of renewable energy in heat and power generation is expected to increase significantly and reach record levels in the coming decades. As a result, emerging energy storage technologies will be key elements in balancing the energy system. To compensate the variability and non-controllability of seasonally generated renewable energy (RES) (daily fluctuations in solar radiation intensity, wind speed, etc.) development of sufficient energy storage infrastructure in the regions will play a major role in transforming RES supply potential into reality. However, local public authorities that are responsible for creating an enabling policy environment for RES infrastructure development in regions encounter numerous challenges and uncertainties in deploying sufficient energy accumulation that often remain unanswered due to a lack of knowledge and on-site capacity, which in turn significantly hinders the regional path to climate neutrality. In this study, the PESLTE analytical framework and composite index methodology is applied to examine the multidimensional factors that influence the deployment of renewable energy storage technologies in municipalities: political, economic, social, legal, technological, and environmental. Developed model is approbated in a case study in a Latvian municipality where four different alternative energy storage technologies are compared: batteries for electricity storage, thermal energy storage, energy storage in a form of hydrogen, and energy storage in a form of biomethane.**

***Keywords* – Composite index; multidimensional factors; municipality; PESLTE analysis; renewable energy storage.**

1. INTRODUCTION

To incentivize the speed of decarbonization, strengthen energy independence by rapidly reducing EU’s dependency of Russian fossil energy resources, EU’s REPowerEU plan has declared to reach at least 45 % share of renewable energy in final consumption by 2030, which is more than a double from around 20 % renewables in 2019 [1], [2]. In terms of electricity generation and supply, this means a major expansion of installed renewable energy capacities. It is estimated that by 2030 at least 50 % of electricity demand will be generated by renewable energy sources, up from a current share of approximately 30 % [3]. The ambitious RES targets are also set for the heating and cooling sector where the EU's “Fit for 55” package set a target to increase the share of RES in heating and cooling at the national level by at least 0.8 % annually until 2026 and by 1.1 % from 2026 to 2030 [1]. Most of this additional renewable

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energy supply will be generated from variable energy sources such as wind and solar energy, which will create significant challenges for the flexibility, security, and price volatility of the entire energy system, putting pressure on the long-term sustainability of the energy sector. Variability and non-controllability of seasonally generated renewable energy (fluctuations in solar radiation intensity, wind speed, etc.) in regions requires for more adaptive and flexible energy system infrastructure [4]. Therefore, enhancing system flexibility and focusing on energy storage solutions will play a major role in transforming renewable energy supply potential into reality.

In the context of moving closer to a prosperous, modern, competitive net-zero greenhouse gas economy and reach Paris Agreement commitments EU developed a Long-Term strategy which analyses different scenarios to achieve 80 % to 100 % decarbonization levels by 2050 [5]. The development pathways differ in level of electrification, utilization of hydrogen and power-to-X technologies (hydrogen, methane, other synthetic gases or liquids). Electrification and significant increase in electricity demand supported with high deployment of renewable energy generation (with high emphasis on solar PV, onshore and offshore wind power) is set out to be the key measure in all the analyzed future decarbonization pathways. Therefore, it is estimated that for future energy system that is highly dependent on RES, high penetration of storage capacities (at least six times larger than currently installed levels) is of primary importance to support the fluctuations of the renewable energy. Subsequently, more in-depth investigation is necessary to study transformational carbon-neutral technological solutions and identify which development pathway will bring the highest contribution to decarbonization of future energy system. Energy storage is highlighted as the key element to accelerate the speed of decarbonization in the European Union [6].

In terms of regional pathway towards green energy transition, municipalities play a key role to enable energy storage deployment in cities and regions. Over the past decade, the role of local public authorities in the national energy system has changed significantly. Whereas in the past local governments relied on general policies of national governments without actively participating in energy system planning, today municipalities have taken stronger institutional role and control over the governance of their local energy system [7]. One of the reasons for the increasing proactive role of local public authorities is the shift from fossil fuels, which are mostly centralized, to renewable energy systems, which are decentralized. Because of the significant increase in decentralized energy systems in local jurisdictions, municipalities have more incentive to play a larger role in their overall energy sector in the region [7].

Although the overall development of national energy systems is influenced by national governments and energy supply companies, municipalities play an important role in shaping energy policy in many countries around the world through the privatization of local utilities [8]. In the Nordic countries, there are a number of municipalities that have privatized their local energy suppliers and developed renewable energy generation facilities (hydropower, wind turbines, methane capture from wastewater, sludge, and landfills) [8]. Another example is Germany, where local utility companies that are owned by municipalities have formed community-based energy cooperatives that have collective participation and responsibility in power generation and distribution in the region [8].

Municipalities take on a wide range of roles, from setting goals, planning, and regulating, to actively participating in the development process as operators, financiers, and facilitators, to being key awareness builders and demand aggregators for the system [8].Municipalities can play a key role in the future energy transition towards renewable energy sources since there are many opportunities for installing renewable energy (e.g., photovoltaic systems) on municipal land, such as on the roofs of public buildings, so municipalities could encourage their citizens to actively participate in the development of the energy system in the region.

Municipalities can also provide support through financial incentives (e.g., tax relief, grants) and setting requirements (e.g., awards) that encourage presumption. In addition, support should not only be financial, but also in the form of advice on renewable energy planning and development [8].

Variable energy requires the development of new and innovative energy storage technologies and alternative development pathways. However, local public authorities that are responsible for creating an enabling policy environment for RES infrastructure development in regions encounter numerous challenges and uncertainties in deploying sufficient energy accumulation that often remain unanswered due to a lack of knowledge and on-site capacity, which in turn significantly hinders the regional path to climate neutrality. This study aims to explore various factors influencing the deployment of renewable energy storage technologies in municipalities faced with the question of which direction to take and what infrastructure investments should be made to move closer to climate neutrality targets.

When investigating multiple factors and impact dimensions, there is a need for a framework that encompasses a broad perspective and incorporates all pertinent aspects without overlooking other essential factors. The PESTLE framework is one of the methods used to address this issue. A study by [9] uses PESTLE analysis approach to investigate the existing challenges in biofuels energy industry development in Europe. Using economic, environmental, socioecological, and geopolitical sustainability factors, the strengths and limitations of various biofuel production and deployment pathways were identified. In a study by [10] the fuzzy EDAS method is used in combination with the PESTLE analytical framework to analyse the efficiency of different renewable energy sources. The application of the method made it possible to rank different renewable energy sources according to their efficiency level, with geothermal and solar energy being ranked the strongest and hydropower the weakest. [11] uses mixed method approach which include PESTLE and SWOT analysis to identify the main factors impacting renewable energy development in Togo. Study finds that the primary obstacles to the implementation of renewable energy in Togo are the limited accessibility of capital, inadequate political support, insufficient infrastructure, and inadequate levels of awareness and education. Literature analysis revealed that PESTLE analysis approach is also used to study waste-to-energy incineration industry [12] and global wind energy deployment [13]. To date, there has been no scientific research examining the use of the PESTLE framework as a means to analyze potential opportunities for energy storage development in municipality settings.

This study applies an innovative model that integrates both quantitative and qualitative assessment methods. The PESTLE analytical framework combined with a composite index methodology is used to compare four different alternative energy storage technologies:

1. Lithium-ion batteries;
2. Water-based sensible thermal storage;
3. Power-to-gas (hydrogen);
4. Power-to-liquid (biomethane).

In the scope of this study, the developed model is approbated in a case study in a Latvian municipality.

2. METHODOLOGY

2.1. General Description of the Methodology

The main objective of this study was to evaluate and compare the potential deployment of four different renewable energy storage technologies in a municipal energy system – batteries for electricity storage, thermal energy storage, energy storage in a form of hydrogen, and energy storage in a form of biomethane. In order to consider and analyse the various factors that influence the development of the energy system in a municipality a multilevel assessment model was created. The methodological framework of this study was based on a combination of PESTLE analysis and composite index methods, using both a quantitative and qualitative assessment approach for data collection of PESTLE indicators. Fig. 1 illustrates the general framework of the research approach. Developed model of this study was approbated in a case study in a Latvian municipality located in Gulbene.

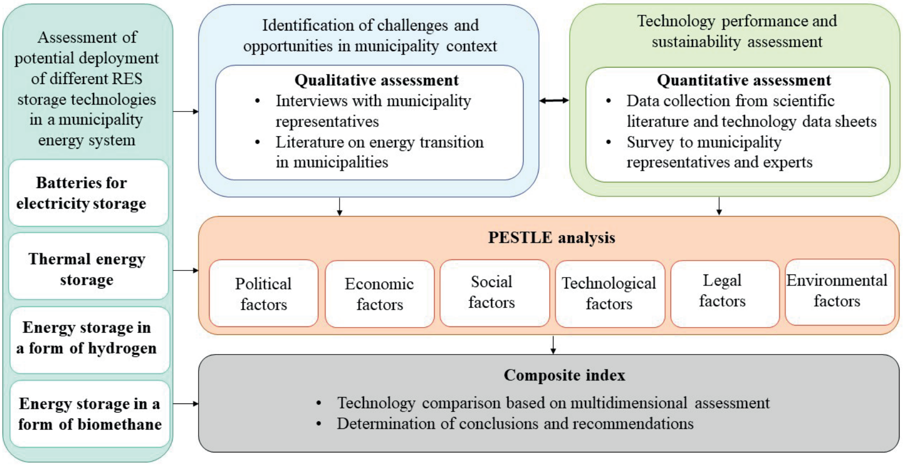


Fig. 1. General framework of the research approach.

PESLTE analysis is a framework used to evaluate multidimensional factors affecting complex systems, specific industries, organizations, or products. Each letter of PESTLE framework encrypts the first letter of the factor included in the analysis – P-political, E-economic, S-social, T-technological, L-legal, E-environmental [9], [14]. This study applied the PESTLE framework to select and analyse relevant factors that influence the deployment of different renewable energy 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.

The quantitative assessment included the collection of data on key performance and sustainability indicators for each energy storage technology. To narrow the scope of the research, lithium-ion batteries were selected from the available different types of different technologies for electricity storage, sensible thermal energy storage technologies were selected for thermal energy storage, and more specifically, hot water tanks were selected in the PESLTE analysis. For hydrogen and biomethane storage, it is assumed that only renewable energy is used in the power-to-gas and power-to-biomethane conversion process.

Survey to municipality representatives was applied to assess different PESTLE indicators from the perspective of municipality. In addition, a qualitative assessment method was used, including both a literature review and interviews with municipality representatives, to strengthen the importance of social, political, and legal indicators in the PESLTE analysis, which are often difficult to quantify.

The steps of the research process in this study are shown in Fig. 2. The overall research methodology consisted of a six-step process. First, a literature was conducted, based on which relevant PESTLE indicators were selected and grouped into six main dimensions – political, economic, social, technological, legal and environmental. Then, data were collected for all the determined PESLTE indicators. Furthermore, the data were processed and used for the construction of composite index. Finally, conclusions and recommendations were determined based on the results of the composite index.

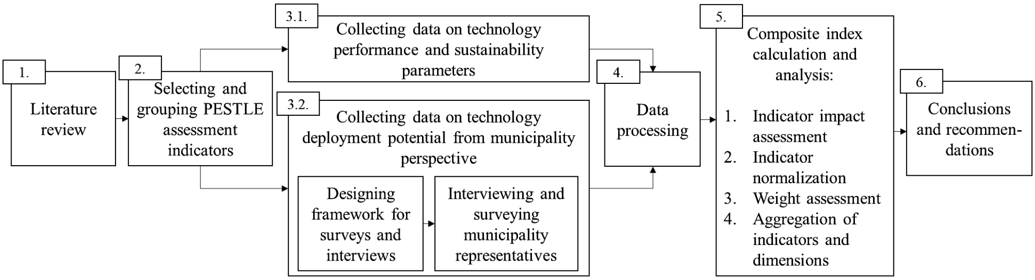


Fig. 2. Steps of the research process.

2.2. Selection and Data Collection on PESTLE Indicators

PESTLE the indicators were selected based on the findings from the literature review on the deployment of renewable energy storage technologies in municipalities and on the availability of data for all four selected alternative technologies. Table 1 shows the selected indicators grouped by their representative PESLTE dimensions.

Data collection on selected indicators was organized in two levels. First level included data collection on technology performance and sustainability parameters. Data were collected from scientific literature [15]–[19] and technology databases such as the European Commission's Energy Storage Database [20], the Danish Energy Agency's Outlook on Energy Storage Technologies [21], technology reports from IRENA [22], [23], technology reports from the European Association for Storage of Energy [24], and other technology outlooks [25]. For several indicators such as CAPEX, OPEX, round-trip efficiency, and environmental impact, the data found in the literature and technology datasets included a value that had a data range. In this study, the mean values of the specified data range were used. In the context of thermal energy, the term ‘round-trip efficiency’ refers to efficiency. For the qualitative indicators, assessment scale was used to quantify the indicators comparing the different technologies. The assessment scale was specified and defined for each qualitative indicator as shown in Table 1. The second level included data collection from surveys and interviews with municipality representatives. The data obtained from the surveys and interviews allowed the study to include the perspective of the regional public authority when analyzing the various technologies.

2.3. Survey and Interviews with Municipality Representatives

In this study, a mixed design of interview and survey method was used. First, a questionnaire was designed with predetermined questions, which were then discussed and completed with the interviewer during the interviews with municipality representatives.

The questionnaire was sent to respondents prior to the scheduled interview date so that respondents had the opportunity to familiarise themselves with the topics and questions to be discussed. Five representatives of the Gulbene municipality in Latvia were surveyed and interviewed. The following municipality representatives were interviewed and surveyed: senior project manager of the Gulbene Municipality Development and Procurement Department, energy manager of the Gulbene District Municipality, advisor to the chairman of the Gulbene Region Municipality on development, projects and construction, senior project manager of the Gulbene Region Municipality, architect of the Gulbene Region Municipality Construction Department. A total of five interviews were conducted and transcribed. The interviews took place in person in March 2023 in Gulbene. Each interview lasted approximately 30 minutes to 1 hour.

TABLE 1. SELECTED PESTLE INDICATORS AND VALUES

Indicator	**Unit of measurement**	**Data source**	**Impact**	**Batteries**	**Thermal**	**Hydro -gen**	**Bio-methane**
Political							
State political initiative and support	Scale from 1-very low to 5-very high	Survey	+	2.8	2.6	1.8	1.8
Municipal priorities and necessity	Scale from 1-very low to 5-very high	Survey	+	3.2	4.2	2.2	1.8
National and international level policy targets	Scale from 1-very low to 5-very high	[25], [26]	+	3	3	2	1
Economic							
CAPEX	EUR/kW	[20]	–	725	309	3500	2400
OPEX	EUR/MWh	[21]	–	2	1.8	30	50
Capital availability for municipal co-financing	Scale from 1-very low to 5-very high	Survey	+	2.6	2.8	1.6	1.8
Social							
Public attitude and knowledge	Scale from 1-very negative to 5-very positive	Survey	+	3.2	3.4	2.2	2.2
Knowledge of the municipality about technology	Scale from 1-very low to 5-very high	Survey	+	3.4	3	2	2
Technological							
Technology level of maturity	Scale from 1- not mature to 5-very mature	[22], [23], [24]	+	4	4	2	2.5
Round-trip efficiency	%	[20], [27]	+	87	77	30	53.5
Response time	time (1-very slow, 5-very fast])	[20]	+	ms (5)	30 sec. – 3 min. (3.5)	< sec – < min (4)	sec (4.5)
Storage duration at full power	time (1-very low, 5-very high)	[20]	+	min–hours (2)	Hours–months (4)	hours – weeks (3)	some weeks (4)

Level of complexity for technology to be integrated in the existing grid	Scale from 1-very low to 5-very high	Survey	–	3	3.2	4.2	4
Legal							
Level of complexity to get environmental permit	Scale from 1-very complicated to 5-very easy	Survey	–	3.6	3.8	3	2.8
Level of bureaucratic burden to get municipal approval	Scale from 1-very low to 5-very high	Survey	–	1.8	2.2	2.8	3
Environmental							
Potential environmental risk	Scale from 1-no risk to 5-high risk	[15], [16], [17], [24]	–	3	2	3	3
Lifetime of technology	Years	[20]	+	15	30	18	30
Environmental impact	gCO_{2e}/kWh	[15], [16], [17], [24]	–	84	15	0	20
Territorial availability for technology installation without impacting environment	Scale from 1-very low availability to 5-very high availability	Survey	+	4.4	4.4	2.2	2.2

At first questionnaire contained the following nine questions asking respondents to assess different indicators for all four energy storage technologies on a defined scale:

- How do you assess the municipality's knowledge about the possibilities of using certain storage technologies in the energy supply of Gulbene district?
- How do you evaluate the state's policy initiative and support for innovation and development of municipal energy systems?
- In your opinion, what are the priorities/needs of the Gulbene municipality for the installation of such technologies in the district?
- What possibilities do you think the municipality would have to co-finance the implementation of the specific technology?
- In your opinion, what is the attitude of society in the municipality towards the deployment of new technologies?
- How would you assess the extent to which the existing energy supply networks in Gulbene would need to be modified to integrate the specific storage technologies?
- In your opinion, would there be an available area and a suitable place on the territory of the municipality to place equipment that would not particularly affect the environment?
- How difficult do you think it would be to get an environmental impact assessment and a permit for certain technologies?
- How difficult do you think it would be to obtain approval to implement a particular development direction, and what would be the bureaucratic burden on the municipality and local authorities?

The following two open ended questions assessing barriers and drivers were asked at the end of the interview:

- In your opinion, what are other barriers to the deployment of renewable energy storage technologies in the municipality, which may not have been mentioned in the survey?
- What else do you think would be necessary to successfully move forward with the implementation of one of these development projects?

Finally, the questionnaire asked respondents to evaluate the impact of all six PESTLE factors where the average results were further used in the weight assessment of indicators during the construction of composite index.

2.4. Construction of PESTLE Composite Index

The values of the PESTLE indicators from Table 1 were used as input data for the calculation of the composite index. The overall construction of the composite index consists of four main steps:

1. Indicator impact assessment;
2. Indicator normalization;
3. Weight assessment;
4. Aggregation.

The procedure and equations for the calculation of the composite index were retrieved from studies by [28]–[30] and adjusted for this specific research.

Indicators are assessed according to their impact on promoting more active deployment of renewable energy storage technologies in the region. Indicators can have either positive or negative impacts. The general rule of thumb for evaluating impact is to consider whether or not an increasing value of a particular indicator would be beneficial to the low-carbon energy system as a whole. For example, greater government policy initiative and support for a particular technology would promote its diffusion, which is why this indicator is considered to have a positive impact. On the other hand, higher initial capital expenditures (CAPEX) would impose some burden on technology deployment, and an increasing CAPEX value would have a negative impact on diffusion. Table 1 summarizes all impacts for each indicator.

After all indicators have been evaluated for their impact on potential technology deployment in the municipality, all indicators are further normalized. The min-max normalization technique is applied to all indicators. The normalization calculation is performed for either indicators with positive or negative impacts. For indicators with positive impact, normalization is performed according to Eq. (1), and for indicators with negative impact, normalization is performed according to Eq. (2).

$$I_{\mathrm{N}}^{+}=\frac{I_{\mathrm{act}}-\mathrm{I}_{\mathrm{min}}}{I_{\mathrm{max}}-I_{\mathrm{min}}}, \tag{1}$$

$$I_{\mathrm{N}}^{-}=1-\frac{I_{\mathrm{act}}-\mathrm{I}_{\mathrm{min}}}{I_{\mathrm{max}}-I_{\mathrm{min}}}, \tag{2}$$

where

I_{N}^{+}	a positive impact normalized indicator;
I_{N}^{-}	a negative impact normalized indicator;
I_{act}	the actual value of an indicator for the particular technology;
I_{max}	the maximum value of an indicator across all the technologies;
I_{min}	the minimum value of an indicator across all the technologies.

After indicator data normalization, indicator weights were applied. Indicator weights were applied at two levels. At the first level, sub-indices were calculated for each dimension, using equal weighting technique for the indicators in each dimension. Each PESTLE dimension sub-index was calculated using Eq. (3).

$$I_D = \sum w \cdot I_{\mathrm{N}}^{+} + \sum w \cdot I_{\mathrm{N}}^{-}, \; w = \frac{1}{n_{\mathrm{I}}} \tag{3}$$

where

I_D the sub-index of a particular PESTLE dimension;
w the value of determined weight of a specific indicator;
I_{N}^{+} I_{N}^{-} normalized indicators in each PESTLE dimension;
n_{I} the number of indicators in a dimension.

Once the values of the individual sub-indices of the dimensions were obtained, the sub-indices were aggregated to form the PESLTE composite index. Expert weights were used to calculate PESTLE composite index expert weights were applied. The values of the weights for each dimension of PESTLE were obtained from the surveys with municipality representatives. Table 2 summarizes the values obtained. The average values were used as weights for each dimension of PESTLE in constructing the composite index.

TABLE 2. SUMMARY OF ASSIGNED WEIGHT STATISTICS

Dimension	**Min value**	**Max value**	**Average value**
Political	0.10	0.60	0.32
Economic	0.20	0.35	0.27
Social	0.01	0.17	0.13
Technological	0.05	0.17	0.10
Legal	0.02	0.15	0.08
Environmental	0.02	0.15	0.09

PESTLE composite index was calculated by aggregating the individual sub-indices and applying the respective weight, according to Eq. (4).

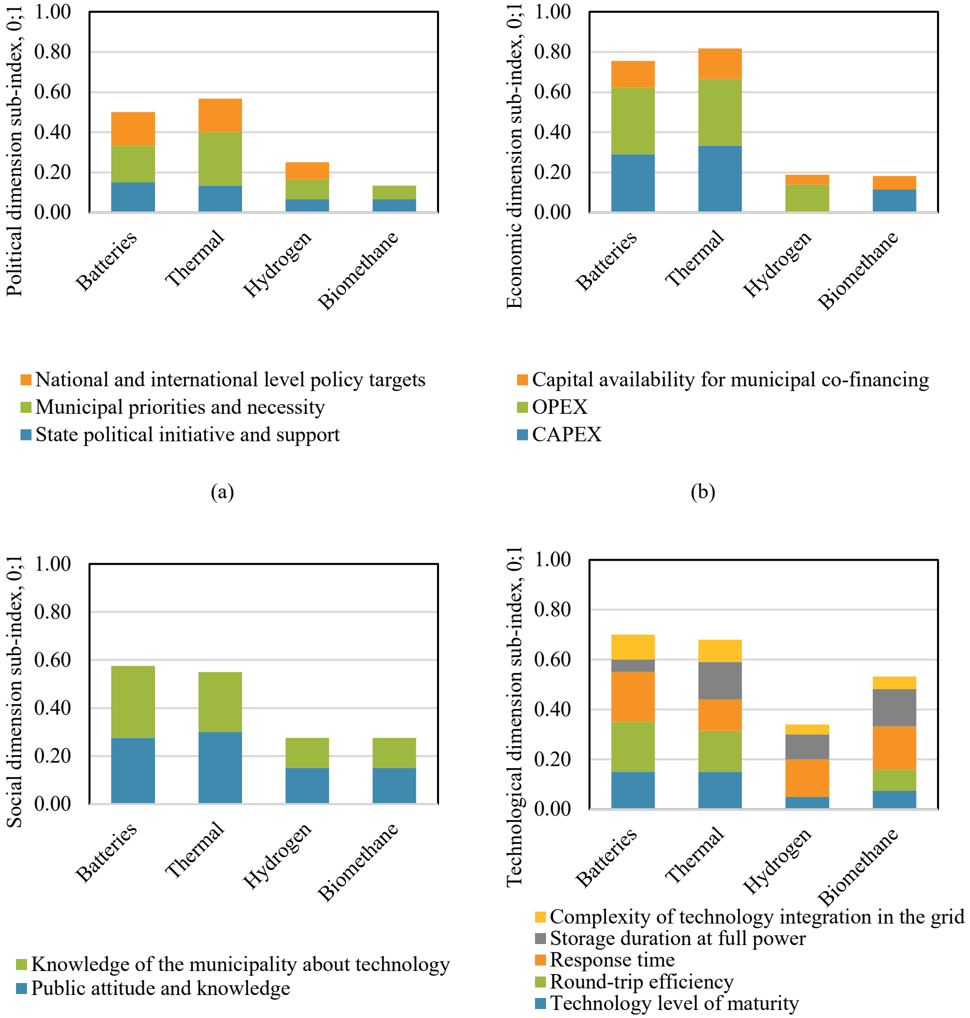
$$CI = \sum w \cdot I_D \text{ , } w \text{ is determined from Table 2,} \tag{4}$$

where *CI* is final PESTLE composite index, *w* is the value of determined weight of a dimension.

3. RESULTS

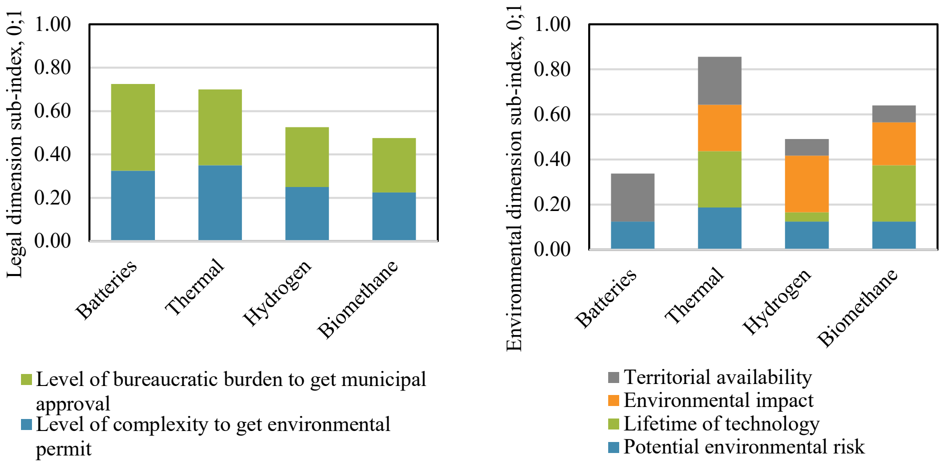
3.1. PESTLE Composite Index Results

The results first represent the values of the subindices of the dimensions (see Fig. 3). Then, the results of the sub-indices were combined into PESTLE composite index which is illustrated in Fig. 4. The results of the individual dimensions are explained in detail below, followed by the analysis of the combined results of PESTLE composite index.


Political dimension sub-index, 0;1
1.00
0.80
0.60
0.40
0.20
0.00
Batteries
Thermal
Hydrogen
Biomethane
National and international level policy targets
Municipal priorities and necessity
State political initiative and support
Economic dimension sub-index, 0;1
1.00
0.80
0.60
0.40
0.20
0.00
Batteries
Thermal
Hydrogen
Biomethane
Capital availability for municipal co-financing
OPEX
CAPEX
Social dimension sub-index, 0;1
1.00
0.80
0.60
0.40
0.20
0.00
Batteries
Thermal
Hydrogen
Biomethane
Knowledge of the municipality about technology
Public attitude and knowledge
Technological dimension sub-index, 0;1
1.00
0.80
0.60
0.40
0.20
0.00
Batteries
Thermal
Hydrogen
Biomethane
Complexity of technology integration in the grid
Storage duration at full power
Response time
Round-trip efficiency
Technology level of maturity

(a) (b)

(c) (d)



(e) (f)

Fig. 3. Sub-indices of PESTLE dimensions: a) Political dimension sub-index; b) Economic dimension sub-index; c) Social dimension sub-index; d) Technological dimension sub-index; e) Legal dimension sub-index; f) Environmental dimension sub-index.

Political dimension sub-index results show that thermal energy storage outperforms the other technologies, followed closely by batteries. Thermal storage scores much higher due to direct municipal priorities and the need to store thermal energy. Since municipalities have less control over the electricity system, they do not feel the benefits of batteries as strongly as those of thermal storage. There is no strong support from municipality representatives towards the potential use of hydrogen and biomethane because the main heat source in the municipality is biomass, not natural gas. In addition, municipality representatives acknowledge that there are currently more government initiatives and support for the integration of thermal energy storage and batteries. There are no strong national policies and regulations focused on supporting and accelerating the development of biomethane and hydrogen storage infrastructure, which is reflected in the results of the political dimension sub-index. At the international level, batteries have stronger policy targets in the EU to support rapid deployment, while thermal energy storage is given less priority compared to batteries. For thermal energy storage, priorities depend more on national governments and their visions. Hydrogen deployment is also highly prioritized at the EU level, while biomethane is less frequently prioritized and there is no strong and focused policy vision.

The results of the economic dimension sub-index show that thermal energy storage and batteries for electricity storage are currently the most cost-effective solutions compared to biomethane and hydrogen. Both initial specific capital investment (EUR/kW) and operation and maintenance costs (EUR/kWh) for thermal energy storage and batteries are significantly lower than for hydrogen and biomethane, which require high investments in infrastructure development and integration into existing energy systems. The capital availability of municipal co-funding for batteries and thermal energy storage solutions is significantly higher due to lower specific investment costs and a reasonable payback period that justifies the economic viability of the technology.

The results of social dimension sub-index show that both overall public attitude and knowledge and knowledge of the municipality representatives about technology is considerably higher for batteries and thermal energy storage than for hydrogen and biomethane. This is due to the fact that municipalities are generally more familiar with these technologies, as small-scale energy storage solutions for electricity and thermal energy are already installed in the region. Municipal representatives acknowledge that there is still much that is unknown about the optimal performance of these technologies and understanding of their benefits, but as they gain experience, they will become more proficient in their understanding and utilize these technologies.

On the other hand, hydrogen and biomethane technologies are less understood and municipality representatives have very limited knowledge about these new emerging technologies. Due to the lack of knowledge, the municipality representatives are skeptical about these solutions, as there are no real examples of best practices in other Latvian municipalities yet, and no basis and certainty has been established for the potential benefits of these solutions.

In general, public attitudes and knowledge about batteries and thermal energy storage tend to be positive, especially now that electricity prices have risen extremely, and the importance of energy self-sufficiency has been elevated nationally due to the global geopolitical situation. In general, people base their overall attitude on familiarity with technology. There are several small-scale thermal energy storage solutions installed in the municipal boiler houses, and people have a positive attitude toward it because they understand the benefits. Public understanding and acceptance of solar batteries has grown recently because of the examples already installed in the region, which are used to justify the investment and explain the benefits to the general public. However, for hydrogen and biomethane, attitudes tend to be negative due to a lack of understanding of these technologies and people simply not seeing how and where these energy sources can be used. These technologies are seen as very new to the public, and there is much that is unknown and no information that easily explains the benefits of these technologies to the general public.

Compared to the other PESTLE sub-indices, the technological dimension sub-index contains a larger number of indicators describing the main factors of technological performance. The results of the technological dimension sub-index show that batteries and thermal energy storage technologies outperformed biomethane and hydrogen storage in the technological dimension sub-index.

This is mainly due to the higher maturity of the technology and the lower complexity of the technology to be integrated into the existing grid for batteries and thermal storage. This means that these technologies are more mature and already commercialized, which significantly increases the overall confidence in these technologies, as their performance has already been proven. However, the opposite is true for hydrogen and biomethane storage: these technologies are mostly still in the research and demonstration phase, and there are few already commercialized and proven solutions. Hydrogen and biomethane storage also require extensive modifications and adaptations to the existing infrastructure to integrate these energy resources into the existing grid, while the integration of batteries and thermal energy storage is much simpler and does not require much additional effort to adapt the grid.

In general, batteries and thermal storage also have higher round-trip efficiency compared to other alternatives. Round-trip efficiency is critical to a sustainable energy system because it represents the fraction of electricity that is stored and later retrieved, characterizing the extent of energy loss in storage [31]. Hydrogen and biomethane have significantly lower round-trip efficiencies, which negatively impacts the overall energy efficiency of the conversion process and the sustainable use of these energy resources.

Response time is another important indicator that characterizes energy storage technologies. Response time is the time required for the entire energy system to provide energy at its full capacity [32]. Batteries show the fastest response time (ms) compared to other technologies where response time ranges from seconds to minutes for hydrogen, biomethane and thermal energy storage technologies. The results of technology sub-index show that the main disadvantage of batteries is the shorter duration of storage at full power compared to other alternatives.

The legal dimension sub-index represents the degree of legal and administrative burden associated with the municipal energy system development project. A higher level of bureaucratic burden increases the time for approval of energy development projects and could therefore lead to significant delays in the transition to a sustainable energy system. The results show that both the bureaucratic burden of obtaining a municipal approval and the complexity to get environmental permit is lower for batteries and thermal energy storage than for hydrogen and biomethane. Due to the significantly higher uncertainty of hydrogen and biomethane, it would be much more complicated to obtain environmental permits to demonstrate that all safety concerns have been addressed and environmental risks have been eliminated. Similarly, because of the higher initial capital investment for hydrogen and biomethane, it would be much more difficult to convince municipality representatives to support these development directions unless reasonable economic justifications are presented.

The results of the environmental dimension sub-index showed that batteries had the lowest value among all technologies, with a value of 0.34. This is due to the shorter lifetime of the technology and the higher environmental impact. In general, lifetime of lithium-ion batteries ranges from 10 to 20 years [20]. Although the average lifetime of batteries is increasing annually due to technological advances, it is still lower on average than other technologies in this study [33].

Considering the entire life cycle of technologies, which includes material extraction, manufacturing, and disposal of the product, batteries were found to have the greatest environmental impact among alternative technologies. The extraction of lithium-ion resources is a highly energy-intensive process that significantly impacts the overall resource efficiency of lithium-ion battery production [34]. In addition, the short life of batteries requires much more frequent replacement of battery components, resulting in higher environmental impacts [15]. There are still many concerns about the sustainable disposal of lithium-ion batteries, as leaks of hazardous substances can occur [34].

Potential risks and damages are also associated with hydrogen and biomethane storage, mainly due to the safety risks of the respective technologies. For biomethane, the risk of methane leakage should be considered. The production and transportation of biomethane poses a risk of methane leakage, a potent greenhouse gas. This can occur from biogas plants, pipelines, and storage tanks [35]. Strict safety requirements must be observed for hydrogen, as hydrogen is a highly flammable gas. In addition, the production of hydrogen requires water, which can pollute local water resources if not handled properly [36]. Thermal energy storage is generally associated with lower environmental risks and potential damage.

According to municipality representatives, there is space and areas in the region for the installation of all the energy storage technologies of this study, although it would be much easier to find suitable areas for batteries and thermal energy storage than for hydrogen and biomethane energy storage, which require more specific conditions. For hydrogen, closeness and availability of RES such as wind and solar power to generate electricity for electrolysis is required, and close access to water resources is recommended. For biomethane, closeness to existing biogas plants and availability of resources for biogas production in the region, such as organic waste, crop residues, animal manure, and others, are required. In addition, proximity and access to existing natural gas infrastructure for potential injection into the gas grid and closeness to water resources to be used in bioreactors are highly recommended for biomethane storage technologies. In terms of technology-specific requirements for specific geographic conditions, less stringent requirements are needed for batteries and thermal energy storage than for power-to-gas and power-to-liquid technologies. For batteries, close access to the power grid and availability of space are required. For thermal energy storage, closeness to the heat source, availability of space and, depending on the storage type, availability of water is required.

Fig. 4 illustrates the overall PESTLE composite index results. 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.

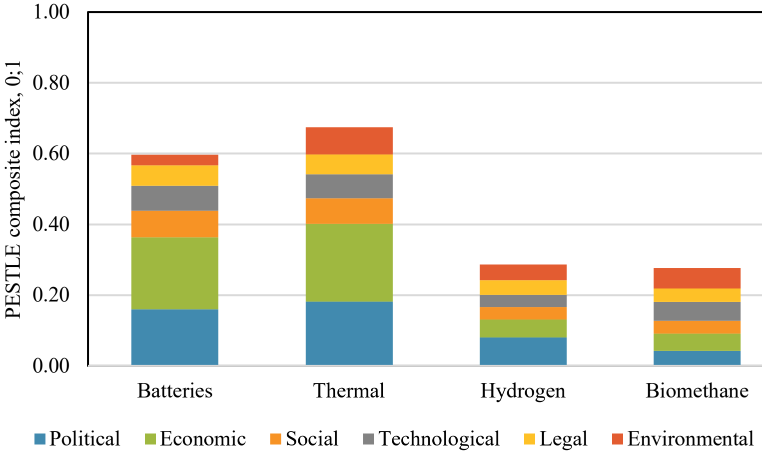


Fig. 4. PESTLE composite index results.

The political and economic dimensions had the strongest influence on the overall results of the composite index, as the weights assessed by the municipality representatives were higher in the index calculation (for the political dimension – 0.32 and the economic – 0.27). As a result, thermal energy storage outperformed the other alternatives, mainly due to its stronger position in the political and economic dimension sub-index. In the case of batteries, the environmental dimension proved to be the weakest position due to the higher environmental impact it causes. However, it did not have a major impact on the overall results of the composite index, as it had an overall weight of 0.09. At the dimension level the highest disparities in the sub-index results were noticed in the economic and environmental dimensions.

Similar results of the PESTLE composite index were obtained for hydrogen and biomethane, as both technologies were found to have similar limiting factors for technology deployment in the municipal context. High capital investment, less targeted policy initiatives and support, and the higher complexity of these technologies to integrate into the existing grid are among the main reasons why hydrogen and biomethane storage lag significantly behind battery and thermal energy storage development.

3.2. Results from the Interviews with Municipality Representatives

The municipality representatives mention that in the current situation it is politically and nationally more important to preserve electricity on a national level than in local energy communities, which would be more efficient. The municipality has less control over the electricity system and the grid in the region, which is quite different for heat generation, which is more at the local level.

To accelerate the regional transition to low-carbon energy systems and make it more cost-effective, it would be beneficial to establish a centralized team of professionals to manage environmental projects, rather than each municipality figuring it out on its own. Currently, one of the biggest cornerstones of the green energy transition is the lack of knowledgeable individuals and professionals to oversee such development projects, which include the development of energy storage infrastructure. It would be more efficient to have a national, centralized program that coordinates green energy transition projects in municipalities with a team of experts to drive these ambitious development projects. Collaboration and knowledge exchange between municipalities would improve in this way, and the process of deploying energy storage in the regions would accelerate significantly.

Knowledge of batteries is higher in municipality than other technologies, as 10 kW batteries are already installed in the municipality building and integrated into the overall solar power system of the building. Although the cost of batteries has decreased somewhat, they are still quite expensive relative to their benefits. These batteries can store about 1 hour of electricity, but in terms of cost, the batteries represent one-third of the total initial capital investment for the solar power plant. In winter, when solar power is not available to charge the battery, the plant draws power from the grid.

Knowledge of hydrogen in municipality is low, but municipality representatives admit that hydrogen production and storage solutions will develop rapidly in the future, and then municipality would have to consider whether to use hydrogen and in which energy consumption groups. It is important to understand what the optimal integration of hydrogen into the current energy system might look like. The municipality assumes that public transportation would be the most appropriate use of hydrogen. At present, hydrogen technologies could be important for large cities as public transportation, but most municipalities are in no hurry to rapidly deploy hydrogen and are waiting for greater certainty in the technology. Since in the municipality region of this case study does not use natural gas in its heating systems, the municipality does not foresee developing biomethane production and storage infrastructure in the near future.

The municipality in this case study uses biomass for heat generation, so the overall share of renewable energy sources in the municipality is considerably high. Most of the government funding available for green energy transition in municipalities is based on the principle of CO_2 emission reduction, meaning that if a new development project can achieve higher CO_2 emission reduction, the higher chance for that municipality is to receive government funding. If a municipality is already highly decarbonized, it is very difficult to obtain funding. And if a municipality cannot demonstrate high CO_2 reduction potential, then the opportunities to obtain government funding are very limited, and a project without government funding is no longer economically viable for the municipality because the payback period is unreasonably long. Therefore, municipality representatives acknowledge that there is very limited ability for municipality to fund such investment projects as investments in energy storage technologies since municipality alone cannot bear the high investment costs.

Municipality representatives mention that there are psychological barriers, such as lack of knowledge about available technologies and their benefits. If the technology is unknown, then municipality tend not to choose it because they need to be able to operate with it and understand in detail how the system works. If the municipality's knowledge level is what it is, then the municipality may not even consider a technology as a possible option because they do not know anything about it. Lack of knowledge also impacts decision making regarding possible future directions in the municipality. If it is not understood how the technology works and the necessary experts and professionals are not available, municipality is afraid of what will happen in operation. Municipality representatives admit that there have already been cases with a simple system like a pellet boiler. It is difficult to find suitable professionals who are able to keep the system operating properly. This could be a big obstacle if there is no one at the plant who can maintain and manage the technology properly.

It is very difficult for municipalities alone to financially support large capital investment projects such as investments in energy infrastructure development. Government support is critical to the regional transition to carbon neutrality. Without state support, these technologies are not economically viable. With state support, municipalities are more open to considering new development pathways. It is also much easier to explain the economic justification for these investments to residents and to gain more public support.

4. CONCLUSION

In this study, a model combining both the PESTLE analytical framework and the composite index method was presented to compare the different energy storage alternatives and their potential deployment in a municipality in Latvia. Using a quantitative and qualitative assessment approach, such as interviews and surveys with municipality representatives, the study sought to quantify the key factors affecting the potential integration of the following four energy storage technologies in a municipality:

1. Lithium-ion batteries;
2. Water-based sensible thermal storage;
3. Power-to-gas (hydrogen);
4. Power-to-liquid (biomethane).

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 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.

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 sceptical 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.

The legal dimension evaluated the degree of complexity 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 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.

Further research could apply the developed methodology in other municipalities, thereby augmenting the study's sample size and obtaining a more comprehensive perspective of extant challenges and motivators in municipalities. Additional indicators could be integrated into each dimension of the PESTLE analysis to further expand the analysis.

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PAPER 8: ENERGY TRANSITION REALITY CHECK: ARE MUNICIPALITIES MEETING THE MARK?

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Energy Transition Reality Check: Are Municipalities Meeting the Mark?

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Abstract **– In order to meet regional and national climate neutrality goals, decentralisation has placed the energy sector under local government governance, pushing municipalities to take a more active role in energy planning and sector decarbonisation. This study attempted to assess the extent to which municipal efforts have been successful in the adaptation of low-carbon energy systems, and what is the current state of municipal initiatives concerning regional energy transitions. A composite 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. 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). Using a benchmarking approach, the main challenges and opportunities of energy transition in the selected municipalities were identified, which could be used as signals in developing concrete municipal sustainability action plans.**

Keywords **– Benchmarking; composite index; energy efficiency; energy transition; energy policy; energy sustainability; municipality.**

Nomenclature

ETI	Composite municipal energy transition index
I_N^+	Positive impact normalized indicator
I_N^-	Negative impact normalized indicator
I_{act}	Actual value of an indicator for the specific municipality
I_{max}	Maximum value of an indicator across all municipalities
I_{min}	Minimum value of an indicator across all municipalities
I_D	Sub-index of a dimension
w	Determined weight of an indicator
n_I	Number of indicators in a dimension
n_D	Number of dimensions

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1. INTRODUCTION

The EU's ambitious path towards becoming the world's first climate-neutral continent by 2050 [1] has shifted the energy sector towards the adoption of new solutions on how energy is produced, supplied, consumed, and, more importantly, managed [2]. As the energy transition pushes towards national energy system decentralization and highlights the importance of the local energy generation framework [3], municipalities are regarded as the primary drivers and change agents of the EU's path to climate neutrality [7]. 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 [4]. Improving energy efficiency and fostering renewable energy resource (RES) adaptation are local matters, and local authorities should provide the right conditions for it, considering the region's specifics, such as geographical conditions and special planning [5], [6]. Sperling *et al.* argued that the new role of municipalities would be to act as strategic energy planners, actively participating in the development of national energy policy and flexibly exploring, for example, new legal or economic incentives [10]. Other studies highlight the role of municipalities in energy transition by arguing that municipalities can reduce costs by independently generating electricity from RES. To achieve this, they should establish a transparent energy transition strategy that encourages the participation of stakeholders from all sectors and collaborates closely with them to execute the necessary changes [7]–[9]. Regional development in the context of the energy transition is multi-level and the identified inhibiting or facilitating factors need to be analysed as a whole, as they are interlinked [10]. The Covenant of Mayors initiative, which includes the development of Sustainable Energy and Climate Action Plans (SECAPs) in municipalities, is at the core of this transformative journey, steering municipalities across the EU to commit to ambitious climate and energy goals [11]. Although there has been a growing interest in analysing municipal energy systems over the last decade [12], there is still a lack of comprehensive tools that could effectively help to identify specific areas for increasing the sustainability of the municipal energy system [13].

Prior research employed different approaches to analyse municipal energy systems and explore potential future development scenarios. Hammerschmid *et al.* presented a municipal energy modelling tool based on massive data sets on Austrian municipalities to analyse the most optimal energy transition strategies in terms of regional economic and environmental impacts towards climate neutrality [14]. Although the tool offers great insights into the municipal energy system, it might be difficult to replicate because of the significant data limitations of municipalities in different countries. Azevedo & Leal used decomposition analysis to assess the contribution of local actions to climate change mitigation by looking at the aggregate change in the local energy system under the individual influence of multiple drivers of change, including externalities [15]. Moreover, Vringer *et al.* developed an operational model with an approach specifically designed to assess the impact of municipal performance, exclusively to assess the link between governance capacity and energy transition policy outcomes [28]. Stennikov *et al.* proposed multiple-criteria decision analysis to assess the state of municipal district heating (DH) system and rank different regions with respect to their DH efficiency [17]. Kleinebrahm *et al.* developed a municipal energy system optimization model to investigate energy transition scenarios in main sectors of municipal economy such as households, industry, services and transport. The authors argue that decision-making tools for municipal energy system analysis are crucial nowadays due to rapidly changing political frameworks [18]. Li *et al.* developed a long-range energy alternative planning (LEAP) model to characterize and describe energy flow and balance between supply and demand of municipal energy system [19]. Fischer *et al.* used the simulation tool EnergyPLAN to carry out a techno-economic analysis of the electricity and heating sectors of the energy systems of Nordic municipalities. The authors argue that a significant carbon reduction in the municipal energy systems could be achieved without increasing costs [20]. Drewello presented an analytical framework – a three-level model – that focuses on the determinants of success of the local energy transition and summarises the complex interrelationships of this process. The basic aspects that were identified as indicators for a potentially successful energy transition were: active citizens, local networking, the ability to adapt the local transmission grid and the deployment of long-term storage technologies [21]. Literature review shows that there is limited research on comprehensive evaluation framework for energy transition evaluation and comparison between the municipalities. Establishing a systematic approach to assess and compare the progress made by municipalities in their transition to low-carbon energy systems is crucial. Different indicators associated with municipal energy transition efforts would enable the identification of specific areas that require improvement in achieving the goal of sustainable energy transition.

This study introduced a novel methodology for municipal energy transition evaluation. This study uses a composite index approach to benchmark sustainable municipal energy transition potential in five municipalities of the Baltic Sea Region: Gulbene municipality (Latvia), Tukums municipality (Latvia), Taurage municipality (Lithuania), Tomelilla municipality (Sweden), and Wejherowo municipality (Poland). This study analyses nine indicators that characterise the transition of municipal energy systems towards more sustainable energy production, supply and consumption. The results provide valuable insights into specific improvement opportunities for each of the analysed municipalities and policy.

2. METHODOLOGY

This study applied a multilevel assessment metric to analyze and compare the energy system sustainability of five different municipalities in the Baltic Sea region – Gulbene, Tukums, Taurage, Tomelilla, and Wejherowo municipalities. This study developed and demonstrated an integrated method for evaluating sustainable energy transition in municipal energy systems. A composite index integrating nine indicators grouped in three key dimensions characterizing the existing levels of municipal energy system decarbonization and efficiency was constructed. The index approach was further used to benchmark the current energy transition efforts of municipalities. Figure 1 illustrates the general framework of the study approach.

The composite index method is widely recognized in the field of sustainability research owing to its numerous advantages [22]. First, it allows for the combination of numerous indicators with diverse units of measurement into one integrated assessment metric. Second, it allows to obtain benchmarks for improved energy monitoring and management. Third, the results are comprehensive and easily interpretative, which is extremely important for communication with policymakers and decisionmakers [23].

Five main steps were taken to construct a composite municipal energy transition index (ETI). The first step involved data collection, processing, and selection of relevant indicators. Municipality energy managers and other representatives provided data for each municipality. Based on the data availability and municipal energy system characteristics analysis, a total of nine indicators were selected for the analysis and grouped in three main dimensions – energy efficiency, energy decarbonization and smart energy systems, as outlined in Table 1.

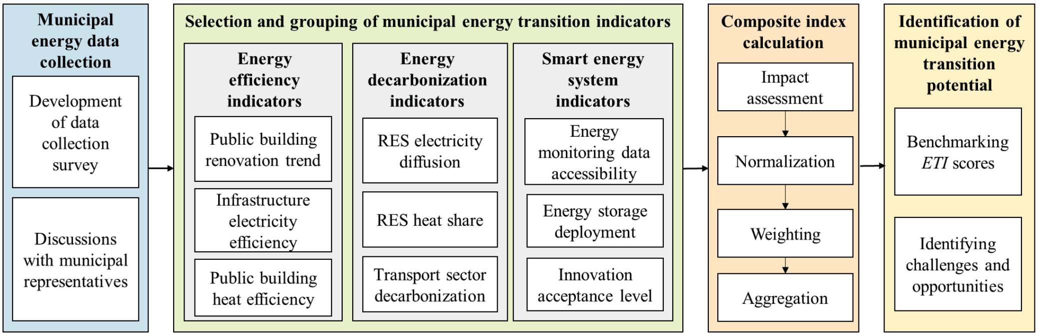

Fig. 1. General framework of the study approach.

All the selected data were data from year 2022 which at the time of the study were the latest available data.

There were two main approaches in data collection for selected indicators – quantitative and qualitative assessment approaches. For quantitative indicators $i_1 - i_6$ actual municipal data was used. However, due to data limitations, an evaluation scale was introduced for the indicators i_5 and i_6. The renewable energy source (RES) heat share indicator (i_5) includes both the renewable energy produced in district heating and the sources used in local heating supply sources of municipal buildings. Due to data limitations, only approximate figures could be obtained for each municipality; therefore, an evaluation scale was introduced, as shown in Table 1. Data limitations occurred in certain missing fuel-consumption-specific figures, where minor approximations had to be taken. Similarly, an evaluation scale was introduced for the transport decarbonization indicator (i_6). This includes fuel consumption in private and public municipal transport. Owing to data limitations on the specific fuel consumption and concrete distances travelled, approximations were made. However, sensitivity analysis revealed that the evaluation scale does not significantly impact the overall outcome or results of the composite index.

Moreover, for qualitative indicators $i_7 – i_9$ an assessment approach using a five-point scale was introduced, as outlined in Table 2. Qualitative indicators were assessed based on the information received from the municipal representatives through private one-to-one discussions and municipal energy data provided.

Second, each indicator was assessed according to its impact on the energy transition. Two main categories were determined: positive and negative impact indicators. An indicator is considered to have a positive impact if its increasing value results in increased sustainability. However, the indicator is negative if its increasing value diminishes the sustainability level. Third, both positive and negative impact indicators are normalized using the min-max normalization technique, according to Eqs. (1) and (2) which were retrieved from [24]. For indicators with evaluation scale (i_5 - i_9), in the normalization minimum value was equal to 1 and maximum value equal to 5, according to predefined scales in Table 1 and Table 2.

TABLE 1. SELECTED COMPOSITE MUNICIPAL ENERGY TRANSITION INDEX (ETI) INDICATORS AND VALUES

Indicator	Explanation	Unit of measure	Impact	Gulbene municipality	Tukums municipality	Taurage municipality	Tomelilla municipality	Wejherowo municipality
Energy efficiency dimension								
Public building renovation trend (i_1)	Proportion of municipal buildings renovated from total heating area of buildings	%	+	51.9	34	21.28	63	67
Infrastructure electricity consumption efficiency (i_2)	Municipal electricity consumption per inhabitants	kWh/inhabitant	–	167.4	147.5	100.6	206.4	172.3
Public building heat consumption efficiency (i_3)	Average heat consumption of municipal buildings	kWh/m^2	–	106.8	132.8	133.6	126.0	92.7
Energy decarbonization dimension								
RES power installation diffusion (i_4)	Installed municipal RES power plants per inhabitants	MW/inhabitant	+	0.47	0.21	1.50	2.60	0
RES heat share (i_5)	Share of produced heat energy from renewable energy resources	Evaluation scale: 5p: 95 %–100 % 4p: 85 %–95 % 3p: 50 %–84 % 2p: 10 %–49 % 1p: 1%–9 %	+	95 %–100 % (5)	85 %–95 % (4)	85 %–95 % (4)	95 %–100 % (5)	1 %–9 % (1)
Transport decarbonization (i_6)	Share of electrical and alternative fuel transportation in municipal transport system	Evaluation scale: 5p: 40 %–100 % 4p: 30 %–39 % 3p: 20 %–29 % 2p: 10 %–19 % 1p: 1 %–9 %	+	1 %–9 % (1)	1 %–9 % (1)	10 %–19 % (2)	20 %–29 % (4)	10 %–19 % (2)
Smart energy system dimension								
Digitalization and energy monitoring data accessibility (i_7)	Level of data quality and complexity of energy data collection	5-point scale, with 5-the highest, 1– the lowest	+	4	3	3	2	3
Energy storage deployment (i_8)	Existing RES storage technologies installed	5-point scale, with 5-the highest, 1- the lowest	+	2	1	1	1	1
Innovation acceptance level (i_9)	Considerations of innovation adaptation such as hydrogen, and its derivatives	5-point scale, with 5 – the highest, 1– the lowest	+	2	2	2	3	4

TABLE 2. ASSESSMENT SCALE OF THE QUALITATIVE INDICATORS OF THE ETI

Indicator	**Explanation**	**Evaluation scale**
Digitalization and energy data accessibility (i_7)	Level of data quality and complexity of energy data collection	5p: High-quality data, easily accessible through digital monitoring systems 4p: Well-maintained systems with access to data with manageable complexity 3p: Data accessibility is adequate with some complexity in data collection 2p: Limited data accessibility, with complexity in collection 1p: Minimal accessibility, with highly complicated data collection
Energy storage deployment (i_8)	Existing RES storage technologies installed	5p: High installation of renewable energy storage technologies 4p: Significant deployment of renewable energy storage technologies 3p: Moderate installation of renewable energy storage technologies 2p: Low implementation of renewable energy storage technologies 1p: Very minimal or no deployment of renewable energy storage technologies
Innovation acceptance level (i_9)	Future considerations of innovation adaptation such as hydrogen, and its derivatives	5p: Strong acceptance and strategies for integrating hydrogen and its derivatives 4p: Positive perception and determined strategies for adopting these innovations 3p: Consideration given to incorporating hydrogen and its derivatives into future 2p: Some hesitancy or limited planning for the integration of these innovations 1p: Minimal acceptance and low consideration for use of these innovations

$$I_{\mathrm{N}}^{+} = \frac{I_{\mathrm{act}} - I_{\min}}{I_{\max} - I_{\min}}, \tag{1}$$

$$I_{\mathrm{N}}^{-} = 1 - \frac{I_{\mathrm{act}} - I_{\min}}{I_{\max} - I_{\min}}, \tag{2}$$

where

I_{N}^{+}	positive impact normalized indicator;
I_{N}^{-}	negative impact normalized indicator;
I_{act}	actual value of an indicator for the specific municipality;
$I_{\max}$	maximum value of an indicator across all municipalities;
$I_{\min}$	minimum value of an indicator across all the municipalities.

Fourth, after normalization, equal weights were applied. This study considers all indicators to be equally important determinants of sustainable energy transitions in municipalities. Finally, the weighted indicators are aggregated into a respective dimension sub-index according to Eq. (3). Following this, ETI is computed as shown in Eq. (4) by combining the values of each sub-index with its corresponding weight. Aggregation is performed in line with [25].

$$I_{\mathrm{D}} = \sum w \times I_{\mathrm{N}}^{+} + \sum w \times I_{\mathrm{N}}^{-}\ ;\ w = \frac{1}{n_{\mathrm{I}}}, \tag{3}$$

$$ETI = \sum w \times I_\mathrm{D} \;;\; w = \frac{1}{n_\mathrm{D}} \;, \tag{4}$$

where

I_D sub-index of a dimension;

w determined weight;

I_N^{+} normalized positive impact indicator;

I_N^{-} normalized negative impact indicators;

n_I number of indicators in a dimension;

n_D total number of dimensions.

For each dimension sub-index and ETI benchmarks were calculated as weighted average value of municipal scores.

3. RESULTS

The results were grouped and described according to the values achieved in each dimension sub-index. The aggregated ETI results and benchmarks are then discussed.

3.1. Energy Efficiency Dimension Sub-Index Results

Figure 2 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 inhabitants, 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 municipality) to 0.28, the lowest (for Tukums municipality), with an average benchmark value of 0.46. Three municipalities showed results below the benchmark: Tukums (0.28), Taurage (0.33), and Tomelilla (0.37). The main cornerstone of the Tukums municipality is the low share of public building renovation and building heat consumption efficiency. Similarly, the Taurage municipality had the lowest share of renovated public buildings and the highest average heat consumption of public buildings. However, the Taurage municipality had the lowest municipal electricity consumption per inhabitant, indicating a higher power consumption efficiency compared to other municipalities. In contrast, the lowest power consumption efficiency was observed in Tomelilla municipality. Although the overall share of renovated public buildings in Tomelilla municipality was considerably high (63 %), the overall average heat consumption of municipal buildings was the third highest (126 kWh/m^2). This could be potentially explained by the colder climate. Although the Wejherowo municipality had the highest municipal building renovation share and lowest average heat consumption, its main challenge is the considerably high electricity consumption of the municipal infrastructure. This could potentially be explained by inefficient public street lighting in the municipal region, indicating opportunities for the replacement of public street lighting. Similarly, the electricity consumption per inhabitant of the Gulbene municipality could be improved. Municipal infrastructure includes municipal buildings and equipment, public street lighting, water supply, sewerage, and other.

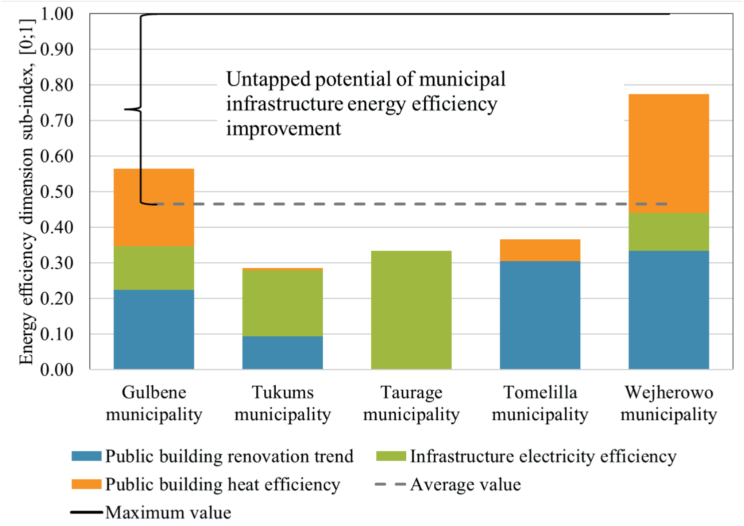

Fig. 2. Energy efficiency dimension sub-index results.

3.2. *Energy Decarbonization Dimension Sub-Index Results*

Figure 3 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 per inhabitants, MW/inhabitants), RES heat share (share of produced heat energy from renewable energy resources, %), and transport decarbonization (share of electrical and alternative fuel transportation in the municipal transport system, %). Energy decarbonization dimension sub-index values indicated the highest range in the achieved results for the municipalities, with highest value of 0.92 (for Tomelilla municipality) and lowest of 0.08 (for Wejherowo municipality). Three municipalities scored below the average benchmark value of 0.44: Wejherowo municipality (0.08), Tukums municipality (0.28), and Gulbene municipality (0.39).

The Tomelilla municipality indicated the highest level of decarbonization in the power, heat, and transport sectors, and therefore reached the highest energy decarbonization sub-index score. There are 35.9 MW installed RES power plants in the municipal region with 29 MW wind turbines and 6.9 MW solar PVs. The heat production in both regions' district heating and individual heating of municipal buildings is entirely based on biomass (wood pellets and chips) and electricity (heat pumps). Moreover, Tomelilla municipality stands out with a high share of transport sector decarbonization. Besides diesel and petrol, municipal transport consumes considerably high amounts of biogas (27.5 thousand kg), HVO (36.8 thousand litres), and electricity (2.5 MWh) for transportation needs. Moreover, according to Tomelilla municipal representatives, the local public transport company entirely uses RME (biodiesel) for their bus fleet, and the public transport fleet is entirely based on renewable energy.

Decarbonization of the transport sector is the main challenge for all municipalities. Besides the Tomelilla municipality, noticeable transport decarbonization efforts are observed in the Taurage and Wejherowo municipalities. In the Taurage municipality, there has been a significant increase in the electricity consumption of municipal private transport (146 MWh in 2022) and public transport (16 electrical buses with a total consumption of 146 MWh in

2022). Similarly, the Wejherowo municipality consumed 230 MWh of electricity to meet public transport needs. Moreover, the Wejherowo municipality considers the purchase of hydrogen buses that can be used for public transport fleets in the future. However, regarding renewable energy deployment for heat and power generation, the Wejherowo municipality showed the poorest results. According to municipality representatives and municipal energy data, no RES power plants are installed in the municipality. Power is produced by the natural gas CHP. In the municipal region, there are only small photovoltaic installations (micro-installations) with a capacity of 4-5 kW, which are individual sources installed in private buildings (mainly single-family residential houses). The heat in district heating in the Wejherowo municipality is produced entirely by fossil fuels, such as coal and natural gas. Furthermore, the results of the energy decarbonization sub-index show that Wejherowo, Tukums and Gulbene municipalities significantly lag behind in installation of RES power plants such as solar PVs and wind turbines in the municipal region. Although both Latvian municipalities possess a considerably high share of RES in heat generation, which is mostly based on biomass utilization, significantly lower amounts of RES power plant installation were observed in the municipalities compared to the other Baltic Sea Region municipalities selected for the analysis.

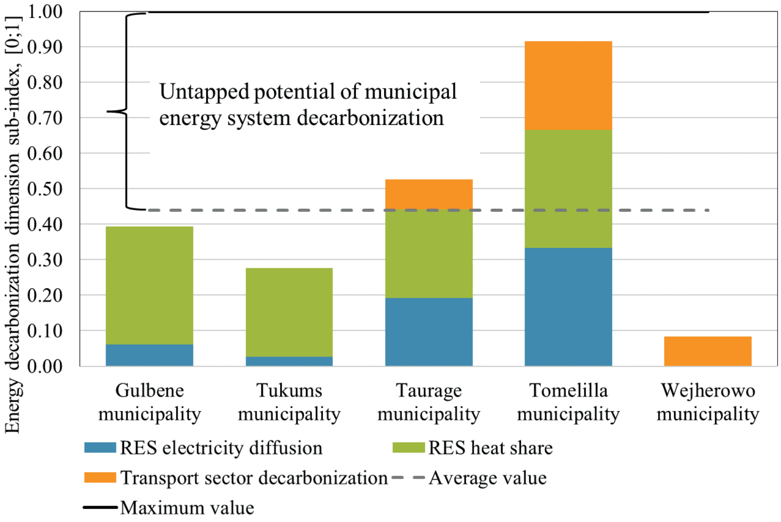

Fig. 3. Energy decarbonization dimension sub-index results.

3.3. *Smart Energy System Dimension Sub-Index Results*

Figure 4 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 municipality and lowest with 0.25 for Tukums, Taurage and Tomelilla municipalities.

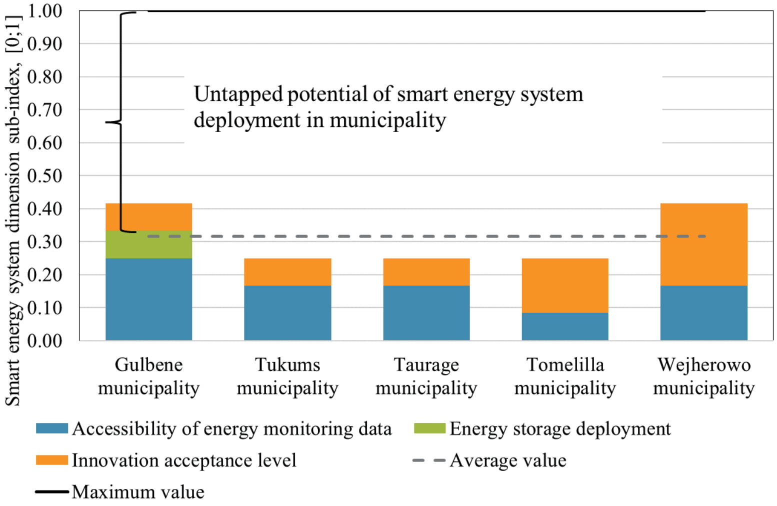

Fig. 4. Smart energy system dimension sub-index results.

The Gulbene municipality stood out as the only municipality that has installed renewable energy storage technologies. There is one small battery system with a total capacity of 9 kWh installed on Gulbene's municipal building, in combination with PV panels. There are also small units of thermal energy storages in individual boiler houses. The Gulbene municipality also demonstrated considerably good data quality and solutions for necessary data acquisition. Regarding innovation acceptance in terms of possible hydrogen, biomethane, and synthetic fuel integration, Gulbene municipality was reluctant. According to the municipal representatives, the Gulbene municipality does not plan to implement hydrogen systems currently because there is no further infrastructure to use hydrogen in the Gulbene region, and it is still expensive and unexplored.

A similar reluctance was also observed by the representatives of Tukums and Taurage municipalities, which do not plan specific actions with regard to hydrogen research and possible integration in municipal infrastructure. However, more positive attitudes and concrete considerations were expressed by the Tomelilla and Wejherowo municipalities with regard to innovation deployment, such as hydrogen and its derivative integration into municipal energy systems. Tomelilla is interested in exploring the long-term potential of hydrogen in the municipality. Most concrete actions were demonstrated by the Wejherowo municipality, where municipal public transport company plans to switch urban transport to buses powered by hydrogen fuel (the first hydrogen bus has already been tested practically in the city for a period of two weeks in December 2023). By 2035, it is planned to purchase 27 zero-emission buses powered by hydrogen fuel. To become completely independent from external hydrogen supplies, investment in the construction of its own hydrogen production and refuelling station in the municipality is also planned.

This study marked that data collection and quality issue is still one of the major challenges and cornerstones of municipalities, which is also reflected in the values of the digitalization and energy monitoring data accessibility indicator (i_7). According to observations, there is no single digital energy monitoring system that covers all economic sectors implemented in municipalities. All selected municipalities encountered significant challenges in data collection. A lack of data monitored directly by the municipality has been observed in several forms. First, data on electricity consumption and production are available only to the national system operator with no direct access to the municipality without special requests, which often involves unnecessary bureaucratic procedures. This issue was observed in the Gulbene, Tukums, and Wejherowo municipalities. Second, district heating and public transport companies are reluctant to provide data that often result in inconsistent and incomplete heat consumption assessments of all sectors of the municipal region. Third, some data are monitored by national authorities and are classified, meaning that municipalities do not have access to these data. This was most prominently observed in the Tomelilla municipality. No direct control over energy data significantly hinders municipal efforts in energy transition.

3.4. Municipal Energy Transition Index (ETI) Results

Table 3 outlines the aggregated results of the ETI and benchmarking values for all three sub-dimensions. Figure 5 illustrates the aggregated results for municipal energy transition index (ETI) of the selected municipalities. The index results illustrate the contribution of each dimension – energy efficiency, energy decarbonization, and smart energy systems. The results show which of the dimensions for a specific municipality is of particular challenge at the moment, and which is the strongest compared to other municipalities, see Table 3.

The aggregated results of the municipal energy transition index (ETI) range from 0.27 the lowest (for Tukums municipality) to highest of 0.51 (for Tomelilla municipality). The average ETI score equals 0.41 where two municipalities scored below the benchmark – Tukums (0.27) and Taurage (0.37) municipalities. Gulbene municipality (0.42) and Wejherowo municipality (0.42) scored above the average benchmark value. However, all municipalities show major untapped potential for sustainable municipal energy transition given that the maximum index value is equal to 1.

TABLE 3. BENCHMARKING RESULTS OF THE COMPOSITE MUNICIPAL ENERGY TRANSITION INDEX (ETI)

	Avg	Gulbene municipality	Tukums municipality	Taurage municipality	Tomelilla municipality	Wejherowo municipality
Public building renovation trend		0.22	0.09	0.00	0.30	0.33
Infrastructure electricity efficiency		0.12	0.19	0.33	0.00	0.11
Public building heat efficiency		0.22	0.01	0.00	0.06	0.33
Energy efficiency sub-index	**0.46**	**0.56**	**0.28**	**0.33**	**0.37**	**0.77**
RES electricity diffusion		0.06	0.03	0.19	0.33	0.00
RES heat share		0.33	0.25	0.25	0.33	0.00
Transport sector decarbonization		0.00	0.00	0.08	0.17	0.08
Decarbonization sub-index	**0.44**	**0.39**	**0.28**	**0.53**	**0.92**	**0.08**
Accessibility of energy data		0.25	0.17	0.17	0.08	0.17
Energy storage deployment		0.08	0.00	0.00	0.00	0.00
Innovation acceptance level		0.08	0.08	0.08	0.17	0.25
Smart energy sub-index	**0.32**	**0.42**	**0.25**	**0.25**	**0.25**	**0.42**
Municipal energy transition index	**0.41**	**0.46**	**0.27**	**0.37**	**0.51**	**0.42**

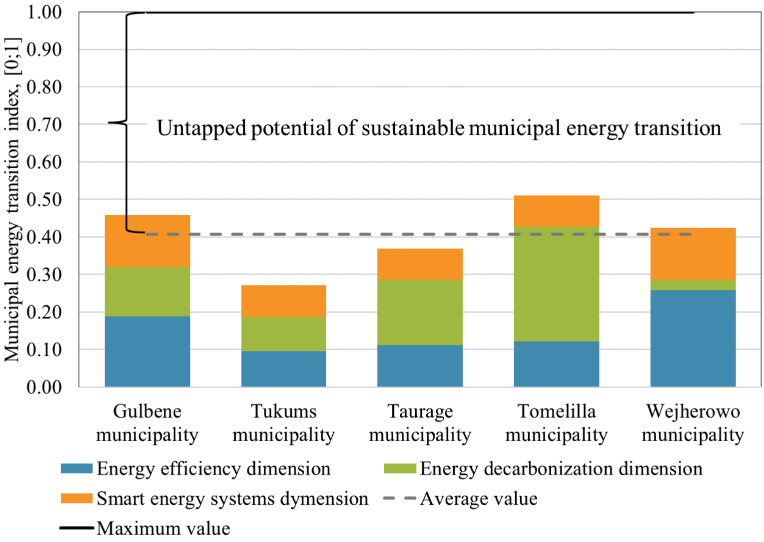

Fig. 5. Municipal energy transition index (ETI) results.

The aggregated results reveal that for Gulbene municipality key strengths are 100 % renewable heat generation system and experience in energy storage technology deployment, i.e., installation of the first battery storage system. However, challenges persist, such as slow progress in transport decarbonization, limited deployment of renewable energy sources (RES) power plants like solar panels and wind turbines, and comparatively high electricity consumption in municipal infrastructure. For Gulbene municipality the identified opportunities and untapped potentials lie in include enhancing energy efficiency further, increasing the installation of RES power plants, electrifying the heat sector through the integration of heat pumps and energy storage systems, and advancing transport sector decarbonization efforts.

For Tukums municipality key strengths lie in the good efforts of heat sector decarbonization and successfully established energy management system. However, the key weaknesses are the low public building renovation rate and the unused potential of RES power plant installation (solar PV and wind power). Key opportunities for Tukums municipality energy transition would be the acceleration of higher RES deployment in power production and transport decarbonization, improvements in infrastructure, and building energy efficiency.

Favorable conditions for wind energy installations, which have led to a greater number of renewable energy source power installations than in other municipalities, and minimal electricity consumption of municipal infrastructure are two of Taurage municipality's greatest strengths. Low rates of public building renovation and transportation decarbonization progress are significant obstacles. Key opportunities for the Taurage municipality include the potential to produce hydrogen and synthetic fuel from surplus wind energy, improving the energy efficiency of public buildings and decarbonizing transport.

The strengths of the Tomelilla municipality are its 100 percent renewable heat generation system, its substantial use of biofuels in the transportation sector, its positive trend in the installation of RES power plants, and its positive trend in the renovation of public buildings. The public building's substantial electricity consumption and the complex nature of energy management and monitoring constitute major weaknesses. Key opportunities include the electrification of the heat sector, the inclusion of storage systems to increase self-sufficiency, and the substantial potential for hydrogen production from excess renewable energy.

For the Wejherowo municipality, the main strengths are the good trend in the renovation rate of public buildings, the considerably low average heat consumption of public buildings and the good efforts in the decarbonisation of public transport. The main weaknesses are the heat generation based entirely on fossil fuels, the lack of municipal measures in the installation of RES power plants (PV panels, wind turbines) and the inefficient electricity consumption of public street lighting. The main opportunities are the utilisation of the untapped RE electricity potential and possible hydrogen production, the massive possibilities of decarbonising and electrifying the heat sector and improving the efficiency of public street lighting.

3.5. Discussion on Policy Implications Based on Results

Study findings reveal a gap in existing policies and approaches used at both at national and regional levels which are consistent with the findings from the prior research. A number of policy initiatives have been promoted and implemented at both EU and national level, but the problem is often implementation rather than development. Policy measures to help stakeholders promote the energy transition include information campaigns, scientific and technological cooperation, tax and production incentives, infrastructure investment, training courses and simplification of administrative procedures [26]. Martínez *et al.* analysed the approach of twenty-eight municipalities in the Netherlands to transition to sustainable heating systems. They concluded that the lack of binding policies to phase out natural gas and the low availability of alternative heating systems should be addressed, while the establishment of centralised support mechanisms and building renovation should be promoted to facilitate this transition in municipalities [27]. Satrovic *et al.* highlights necessity of policies such as funding support, cooperation, monitoring, capacity building and knowledge sharing as key to regional sustainable development [14]. Traill & Cumbers found that municipalities need both financial, political and knowledge gap mitigation support to implement energy transition related change strategies. Sustainable financial and political support are key things that enable municipalities to implement novel solutions and fully invest in the energy transition [29]. Research argues that it is an illusion that energy transition will automatically reduce energy bills and cut emissions. The benefits depend on how energy policies are implemented and enforced [12].

4. CONCLUSION

In this study, developed composite municipal energy transition index which incorporated nine different indicators grouped into three main dimensions – energy efficiency, energy decarbonization, and smart energy systems. Five different municipalities were analysed and compared with the index and sub-index benchmarks of each dimension.

The results highlight various challenges of the municipal energy transition. Transport decarbonization 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.

The method presented is highly dependent on the availability of data. The study has shown that the monitoring and collection of energy data in municipalities is still a major problem that should be given special attention at national level. Barriers to the availability and accessibility of data should be removed at national level. The municipal energy system cannot be assessed and planned if the existing situation cannot be properly evaluated on the basis of reliable data. The results of this study will be integrated into a system dynamics model to analyse the dynamic relationship between the factors and their impact on the local energy transition.

ACKNOWLEDGMENT

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PAPER 9: WHAT DRIVES ENERGY STORAGE DEPLOYMENT IN LOCAL ENERGY TRANSITIONS? STAKEHOLDERS’ PERSPECTIVE.

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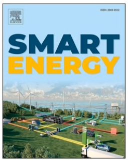

What drives energy storage deployment in local energy transitions? Stakeholders' perspective

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ABSTRACT

The global shift towards decentralised energy systems has assigned municipalities a key role in achieving national climate neutrality objectives. As the main stakeholders in the local energy transition, municipalities are responsible for the decarbonization of the local energy system through the extensive integration of renewable energy sources into existing systems. However, this integration requires new approaches and system adjustments, such as energy storage deployment, to satisfy the variable nature of renewable energy sources. The integration of novel solutions, such as energy storage, is difficult because of the diverse range of stakeholders involved, each with their own perceptions and expertise. This study uses the Fuzzy Cognitive Mapping (FCM) methodology to analyse the mental models of different stakeholders regarding their perceived importance of different factors influencing the implementation of energy storage in municipalities. The approach of this study enables a better understanding of municipal energy systems and its dynamics. The results reveal that support schemes such as subsidies and awareness campaigns are key to all stakeholders. Municipalities tend to focus on local needs and technological solutions, while energy experts prioritize technical aspects and national policies. Municipalities address challenges linearly, missing interconnections, whereas energy experts consider feedback loops and system requirements. The study highlights the need for common ground to drive effective policy and infrastructure development. The results could be used to facilitate discussions with policy makers on why energy storage is important and what policy measures should be considered to accelerate its deployment.

1. Introduction

The EU has pledged to become a climate-neutral continent by 2050, driving the need for accelerated decarbonization across all economic sectors [1]. The process of decarbonization primarily involves a shift from reliance on fossil fuels to a major expansion of renewable energy sources [2]. 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, centralised fossil fuel power plants to decentralised, smaller renewable energy generation plants [3].

As a result of the decentralised 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 [4]. Municipalities are both consumers and energy planners, providers and advisors for their energy end-user groups [4,5]. Municipalities own and operate regional energy facilities due to the dispersed nature of renewable energy generation and the decentralised structure of the energy sector [2].Therefore, municipalities play a central role in the energy transition and in achieving climate neutrality [6,7].

The rising utilisation of renewable energy sources presents energy system operators with significant challenges, since the switch to these variable sources requires a larger degree of flexibility and introduces more complexities into energy system infrastructures [8]. 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

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crucial. The inclusion of energy storage is of extreme significance in facilitating the shift towards sustainable energy systems that mainly depend on renewable sources [9]. 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, more flexibility, and helps to the reduction of emissions [10]. This energy transformation requires municipalities to adapt to smart energy systems, which focus on merging the electricity, heating, and transport sectors, alongside various storage options, to create the necessary flexibility for integrating large penetrations of fluctuating renewable energy [11].

The increasing challenge of integrating smart energy systems and snew technologies, such as energy storage solutions, into municipal energy infrastructures has encouraged inquiries on the factors that impact this process. Moreover, despite the generally increased activity and engagement of municipalities in direct energy planning, there remains considerable confusion regarding their exact roles and expectations in achieving climate and energy goals, which are often unclear [12]. Most studies and analyses have focused on experts in energy system modelling and a centralized planning viewpoint rather than on local energy suppliers and representatives of energy planning in cities and municipalities [13]. Therefore, there is a need to examine the roles played by various stakeholders in the development of regional energy infrastructures.

The strategic planning and development of municipal energy infrastructure involve multiple stakeholders, including energy producers, suppliers, transmission system operators, regulatory agencies, environmental advocacy organizations, residents of the municipal territory, and other relevant parties. Each individual has their own distinct mental models, comprehension, and perspectives. In order to facilitate successful collaborative governance [6] and the execution of the most optimal solution, it is essential to comprehend the needs and priorities of each stakeholder group involved. In the context of the local energy transition, energy storage deployment is seen as an emerging solution that contains numerous ambiguities which, if not resolved, could hinder the regional path to climate neutrality.

This study aims to investigate the complex interplay of diverse stakeholders in the municipal energy sector development that includes energy storage integration in local energy systems. This study applies Fuzzy Cognitive Mapping (FCM) methodological approach to investigate the perception of factors influencing the deployment of energy storage in municipalities by different stakeholders.

A cognitive map, or a mental map, is an externalized representation of a mental model, a person’s mental representation of reality, and his or her assumptions about how the world works. Mental models can often be taken as an intermediate step toward discovering individuals’ presumptions of the outside world [14]. Senge’s learning organization framework emphasizes the necessity of mental models for personal mastery, as well as the critical role of revealing assumptions and developing shared visions in overcoming complex problems such as local energy transition [15]. Understanding the assumptions and mental models of different stakeholder groups can also help to reduce conflicts and disputes in various socioeconomic contexts and group settings [16].

The results of this study could help facilitate discussions with different stakeholders on why storage is important and what policies should be considered to accelerate its deployment. The findings could be further applied to more efficient energy policymaking.

2. Literature review

2.1. Theoretical background & application

Fuzzy Cognitive Mapping (FCM) is a valuable methodology for strategic-level modelling that integrates qualitative and quantitative research methods [17]. FCM enables the creation of qualitative static model which may then be converted into a semi-quantitative dynamic model [18]. FCM was first proposed by Bart Kosko in 1986 as a method for organising expert knowledge using a soft systems programming approach. This approach incorporates the concept of fuzziness, which is said to resemble the decision-making process of the human mind [18].

Fuzzy Cognitive Maps (FCMs) serve as a means of representing the causal perception of either an individual or a collective group through the use of fuzzy-graph structures [19]. The representation of causality between various notions is carried out using a fuzzy connection on causal concepts, with mathematical explanations being generated from constructed FCMs. This approach enables the construction and advancement of a knowledge base by systematically aggregating many FCMs [19].

In basic terms, in academic research FCMs are representations of mental models of the research problem being studied, which serve to define essential system components and their relationships, as well as determine the system’s dynamics if parameters in system components are altered [20]. FCM can be used to study such research problems such as climate challenges or social problems where FCMs are used to model system complexity. FCM has the advantage of being able to cope with a high level of uncertainty and cases with limited empirical data [21]. According to the principles of constructivist psychology, a FCM model uses nodes to symbolise concepts, while arrows connecting these nodes indicate the perceived links and causation that exist between them [17, 22].

Combining intuitive and formal approaches, FCM provides a promising method for developing global, multi-perspective scenarios [23]. Advantages of the method include its ability to deal with uncertainty and its suitability for long-term assessments with limited data availability [24,25]. The study by Bohvalovs et al. (2022) showcases the wide applicability of FCM in modeling dynamic systems, emphasizing its simplicity, flexible design, adaptability, and user-friendliness. FCM proves effective for studying complex systems by integrating expert knowledge and literature data, particularly in understanding human behavior, decision-making, and process influence [26].

FCM is a versatile tool that finds application in various domains, encompassing the analysis of managerial processes such as information system planning, product planning, political modelling, as well as other fields like healthcare and creative industries. FCM insights are frequently employed in academic research to evaluate decision-making processes and gain a comprehensive understanding of managerial actions. FCM approach places particular emphasis on identifying and analysing the similarities and differences in perspectives among various stakeholders [23]. FCM allows to identify both shared and divergent perspectives of different stakeholders, illuminating patterns across various factors [27]. The explicit and standardized representation of stakeholder knowledge opens avenues for collaborative learning, consensus identification, and addressing conflicting viewpoints [28]. FCM often is used for comprehending complex social-ecological systems [29]. For instance, Blewett et al. (2021) findings in research delving into mental models and FCM reveal conflicting social concepts that impact outcomes in ecologically sensitive conservation areas [30]. Alipour et al. (2019) conducted a study suggesting that FCM will have widespread applications in various scientific fields in the future, such as energy, management, climate change, environmental and ecosystem studies, regional planning, medical, medicine, engineering, and social studies [31].

In recent years, the practice of involving stakeholders in environmental decision-making through modeling has gained substantial attention. Programs centered on stakeholder participation within modeling frameworks aim to bolster participatory planning efforts, although concerns about duplicated work have surfaced. To amplify participatory modeling, the "Mental Modeler" software architecture was introduced by Gray et al. (2013) which was developed on the basis of FCM approach. This innovative framework presents a means to bridge the gap between scientific insights and stakeholder involvement, facilitating more effective decision-making processes. Modeling assumes a pivotal role in adaptive management strategies, serving three key objectives: elucidating issues, fostering communication among stakeholders, screening policies, and identifying knowledge gaps. Nonetheless, practical implementation often grapples with challenges stemming from the communication disparity between scientists and stakeholders, potentially hindering efficacy. In the realm of environmental planning, this study accentuates the significance of engaging stakeholders who possess qualified expertise [20].

2.2. Literature review on previous studies applying FCM method

Employing FCM for the analysis of intricate environmental issues can foster effective communication among stakeholders, experts, and policymakers [32]. FCM modeling is found to be useful in policy planning where a study by Nikas et al. (2019) used FCM in Greece to evaluate energy efficiency policy strategies, mainly focusing on behavioral change in the residential sector. The results highlighted the promise of using FCM for policy design and evaluation, providing nuanced insights for enhancing energy efficiency. This approach enables capturing and distilling domain experts' knowledge for informed policy decisions [33]. Another study conducted by Gutiérrez et al. (2017) acknowledges the valuable application of FCMs in policy planning and monitoring. The study highlighted the significant value of FCMs in decision-making, particularly in simulating prospective policy scenarios [34]. Moreover, research by Ziv et al. (2018) demonstrated how FCM can effectively capture diverse expert perspectives on complex policy changes, aiding in the identification of crucial concepts and interactions for informed policy decisions [35].

According to findings from a study conducted by Gray et al. (2015) FCM approach encourages shared participation in decision-making processes. FCMs not only allow stakeholders to contribute to decisions but also facilitate dialogues with governing bodies, management entities, and external parties seeking comprehension. The capacity of FCMs to incorporate preferences and values proves advantageous in situations where discordant values impede negotiation [36].

FCM can help to identify the barriers related to existing challenges in energy and sustainability policies. For example, in a study by Nikas et al. (2020) Using a structured FCM framework, stakeholders identified various risks linked to this energy transition. Barriers highlighted included the potential lasting impacts of an ongoing economic recession, limited public acceptance of renewable energy initiatives, regulatory instability, high technological costs, and unfavorable policy direction that could lead to technological lock-ins [37]. Moreover, in a recent investigation conducted by Dong et al. (2023), a FCM model was acknowledged as a valuable tool for improving the identification of risk-related elements and creating a market association network too, specifically focusing on carbon-related factors [38]. Moreover, FCM offers a promising way to develop holistic, multi-perspective scenarios by combining intuitive and formal approaches [23]. Furthermore, FCM proved to be useful in identifying suitable processes and recognizing result challenges [39].

The study by Özesmi U. & Özesmi S. (2004) agrees that application of FCM enables the development of better conservation strategies and management plans which is particularly important when investigating environmental policy challenges [40]. FCM has a potential to serve as comprehensive decision support tool to support better decision making and development of effective environmental policy [41].

The FCM technique is effectively used in combination with other methods such as system dynamics (SD) modelling. Pereira et al. (2020) employed this dual technique of FCM and SD to substantiate a decision-making procedure that effectively tackles the intricate decision problem being examined [42]. The framework of the FCM method is in line with the general principles of system dynamics. For instance, Vasslides and Jensen (2016) define FCM as models that depict the functioning of a system based on its main components and their causal relationships. These components can be both tangible and intangible, both of which are equally important for understanding system behavior [43].

Giordano et al. (2020) in its study chose to use FCM due to its ability to model system dynamics, even when dealing with qualitative connections or lack of data for complex equations. However, the study revealed that while the FCM's causal structure was easily understood by stakeholders and supported discussions, participants expressed uncertainty about the results of FCM scenario simulations [44].

3. Materials and methods

3.1. Multi-level stakeholder cognitive mapping approach

To use models based on human knowledge to solve problems, a multi-level cognitive mapping approach was used. Cognitive maps can be created for virtually any problem or system. These are qualitative models of a system consisting of variables and the causal relationships between them. Variables can be physically measurable, such as energy consumption or energy price, and abstract, such as willingness to implement a specific technology or knowledge about a specific technology. Variables and causal relationships are determined by the map maker, assigning causal relationships a subjectively determined relative strength on a scale from −1 to +1. The compiler also indicates the direction of causality, indicating which factor affects which [5,40]. Cognitive mapping offers several advantages to modelling, including the ability to collect variable patterns, model relationships that are not precisely known, have multiple feedback loops, and pool knowledge from different parties and use different policy options. Cognitive maps are suitable tools for modelling complex relationships between variables. They are also used in cases where it would be useful to have a modelling tool that would determine the perceptions of the parties involved and help model their possible actions under different policy scenarios, as well as when it would be useful to have a tool that would combine expert knowledge for problem analysis and be able to model different policy options, allowing gain insight into the consequences of possible decisions. Using this tool, one can examine maps of decision-makers and stakeholders, compare their similarities and differences, and discuss them [5,40].

This study used the fuzzy cognitive map approach. The term "fuzzy cognitive maps" was created by Kosko (1993), who was the first to calculate the outcomes of individual cognitive maps and model the effects of different policies using a neural network computing method [6,45]. The fuzzy cognitive map differs from a simple cognitive map, with weights assigned to links between elements in the system. Simple cognitive maps have only three possible strengths: 1, 0 and −1 for the links between the elements. The value 1 represents the positive influence of the driver element on the receiver element, in which a change in the driver element (either increase or decrease) has the same effect on the receiver element, whereas −1 has a negative influence of the driver element on the receiver element, in which a change in the driver element (either increase or decrease) has the opposite effect on the receiver element. Zero indicates that there is no connection between two elements. However, fuzzy cognitive maps use fuzzy logic, meaning that the strengths between elements can be any real number in the range $[-1,1]$. The participants link the factors in their mental models by determining their relationships. The factors included in the model can have a positive, negative, or no relationship. The rule of thumb for determining the relationship is as follows: if an increasing value of one factor increases the value of the other connecting factor, the relationship is positive. If an increasing value of one factor decreases the value of the other factor, then the relationship is negative. Each stakeholder may perceive the relationship between the factors differently [40].

When creating cognitive maps of stakeholders, there can be an unlimited number of knowledge sources with different degrees of knowledge and competence, all of which can be combined into one cognitive map. Likewise, the number of experts or concepts is not limited. Stakeholder cognitive maps provide qualitative information and do not involve parameter estimation; therefore, they are a convenient tool for

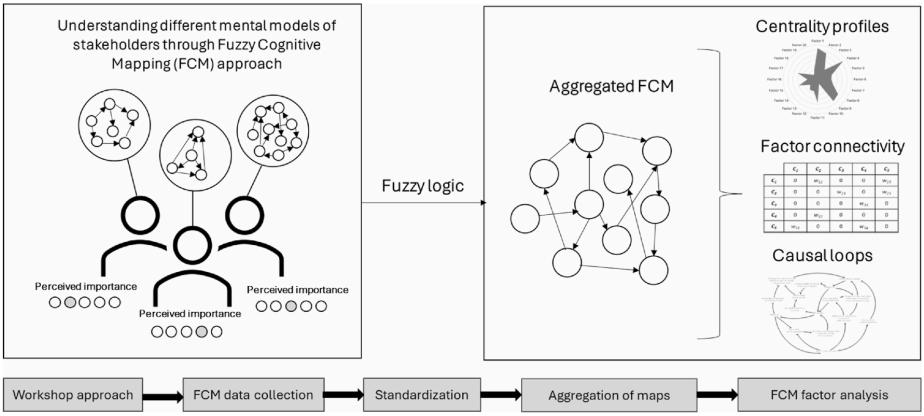


Fig. 1. Multi-level stakeholder cognitive mapping methodological approach, adapted from Ref. [46].

Table 1
Summary of key parameters of mental models by main participant segments.

FCM data collection source	Participant segment	Number of models	Number of factors	Number of connections	Density	Connections per component
First workshop	Energy experts	9	24.6	43.6	0.09	1.80
	Researchers	7	15.1	29.4	0.15	1.99
Second workshop	Stakeholder groups	10	13.1	22.4	0.15	1.71

predicting various models and representing changes in model behavior. The mapping approach can be used to model perceptions and social ideas regarding how the system works. The map does not represent quantitative predictions but represents what will happen to the system under different simulation conditions. The simulations can be performed quickly and easily. Although the cognitive maps of stakeholders do not replace statistical methods and do not represent real-valued parameter estimation, they are excellent for generating hypotheses and evaluating data [5,40].

The multi-level stakeholder cognitive mapping approach used in this study follows several research steps, as illustrated in Fig. 1. 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. The individual mental models were then compiled, standardised and aggregated. The consolidated mental models were analyzed in detail to determine the key impact factors for the deployment of energy storage in municipalities, the connectivity of the factors and the centrality profiles.

3.2. FCM data collection through workshop approach

Two workshops were organised to collect FCM data and analyse the different perceptions of stakeholders. There was a wide variety of stakeholders included in the workshops, both with a deeper understanding and knowledge of energy systems, as well as stakeholders without in-depth knowledge and understanding of the specifics of the local energy system operation. The stakeholders of the mental model workshops involved were from five main groups of expertise: research organizations, municipality representatives, energy clusters and consultancies, local infrastructure providers, and sectoral agencies. The main focus of the workshops was to gain insight from the involved parties about the technical, economic, social, and environmental aspects that influence the development and implementation of energy storage technologies in municipalities. The aim of the workshop was to understand how target groups and energy experts perceive the barriers and opportunities for energy storage implementation in local energy systems. Two different approaches were used in both organized workshops.

The first workshop was held online and comprised a total of 19 participants. There were two groups of participants: first, energy experts working in the field of energy sector development, energy transition, and energy decarbonization; second, researchers working in a field not related to the energy sector. During the workshop, participants worked individually and were asked to build their own mental models. Each participant built the model individually without discussions between other participants and without knowledge of how the individual models of other participants looked, what factors were included, and what connections and strengths were chosen. This was done in this way to avoid influencing the opinions and perspectives of the other participants on the problem examined.

The second workshop was held on-site and comprised 23 participants, who were grouped into groups of 2–3 participants. The participants were all local energy transition stakeholders representing different fields: municipal representatives, municipality energy service providers, energy clusters and associations, and sustainability research organizations. The participants were asked to work in groups and develop their mental models.

Both workshops used the same workshop methodology for gathering FCM data. Workshop participants were first introduced to information about mental models and systems thinking. The process of mental model building was explained together with an easy example of preparing participants for mental model-building exercises. Afterwards participants were asked the following three questions: (1) What factors affect energy storage implementation in municipalities? (2) What social and environmental factors influence energy storage implementation in municipalities? (3) What policies could governments and local public authorities implement to facilitate the implementation of energy storage technologies in municipalities?

Each participant had to fulfil three tasks after each question. Name factors (both tangible and intangible) that influence the system being analyzed. Describe the connections between the factors by connecting them with arrows. Decide on the polarity and strength of each of the

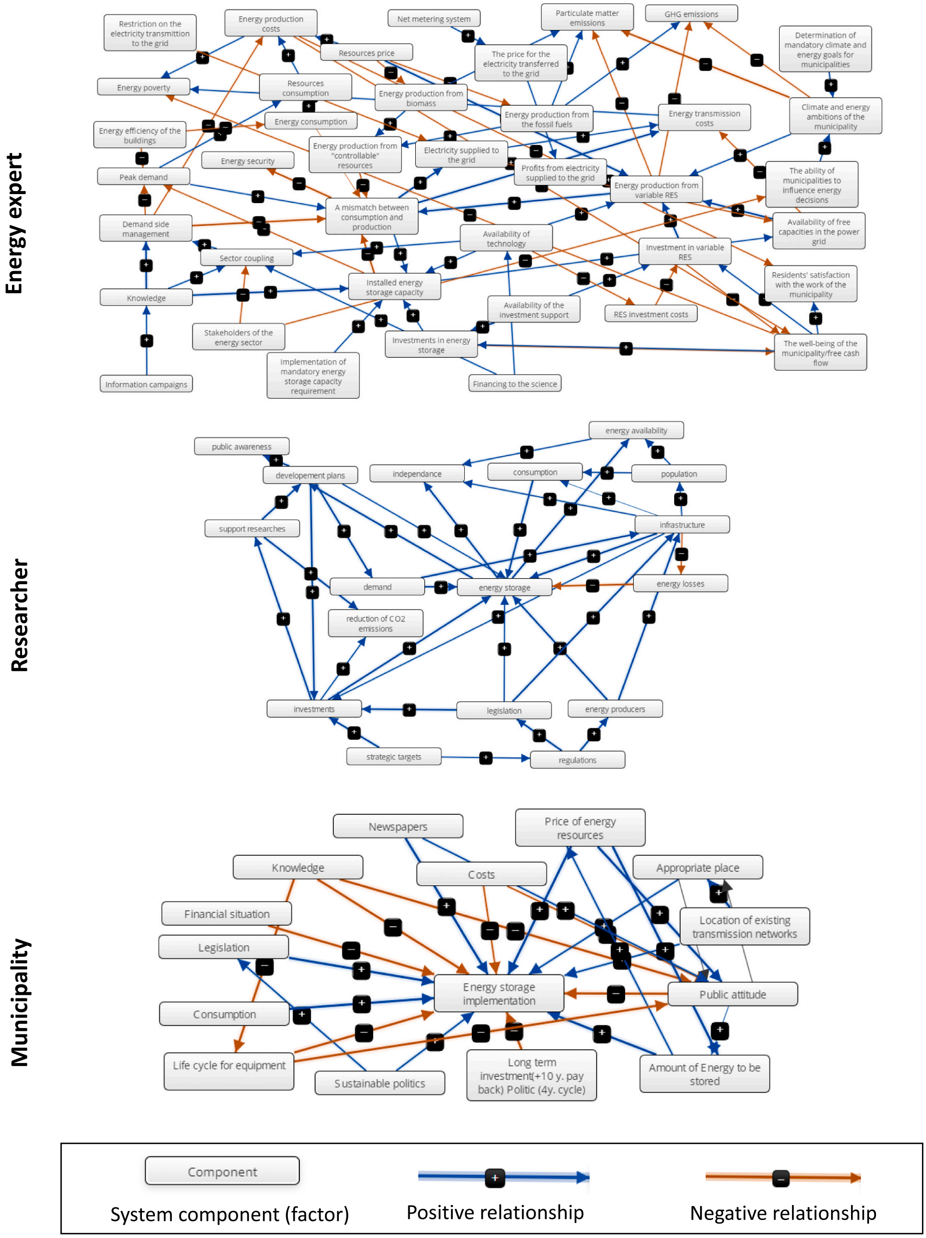


Fig. 2. Examples of mental models of energy expert, researcher, municipality representative, created using mentalmodeler.com online tool [18].

connections. The final versions of the mental models developed were entered by the participants on the mentalmodeler.com website. All the models received were then analyzed, condensed and combined to provide an overall view of the stakeholders.

3.3. Standardization and aggregation of maps

Understanding intricate maps is challenging, and dealing with twenty, thirty, or more variables hinder the ability to gain meaningful insights from the system. Complex maps must be simplified for better comprehension. Map condensation and aggregation is used to better explain the structure of individual cognitive maps.

There are two types of aggregation: quantitative and qualitative aggregation. In quantitative aggregation, a graphical representation of the cognitive map is drawn, and the strong components are visually defined as subgraphs. In qualitative aggregation, elements can be

Table 2
Categories of factors mentioned in mental models and their notations.

Notation	Category		
D1	Energy storage implementation	D11	Policies - support
D2	Knowledge, familiarity & awareness	D12	Policies - knowledge & awareness raising
D3	Energy demand	D13	Energy surplus
D4	Energy infrastructure (production, transmission, distribution)	D14	Energy dependence and security
D5	Energy price	D15	Funding availability (without support)
D6	Technology costs	D16	Occurrence of extreme circumstances
D7	Financial benefits	D17	Citizen's opinion
D8	Willingness and readiness to adapt	D18	Technology solutions
D9	Climate and energy targets	D19	Environmental impact
D10	Policies - taxes	D20	Territory availability
D11	Policies - support	D21	Other

combined into categories represented by a larger encompassing variable. Qualitative aggregation was used in this study to standardize and condense the mental models from the workshops. Furthermore, individual elements from mental models are combined into carefully defined categories. Similar concepts mentioned in the models were clustered together. Based on the defined categories, each individual cognitive map was simplified by replacing the original elements with defined categories. The standardisation and clustering were carried out by the authors of this study. Based on the defined categories each individual cognitive map is simplified by replacing the original elements with predefined categories [28]. Appendix 1 contains an overview of all the factors mentioned by the participants and their clustering into the predefined categories. The categories were determined by the authors of the study manually using Microsoft Excel.

The condensation of the maps was performed in several steps. First step is conversion of the individual mental models made in "Mental modeler" from graph into adjacency matrix. When the mental model graph is converted into an adjacency matrix, all relationships between the elements and their weights are stored in the matrix. The next step was to simplify the model based on the defined categories. The adjacency matrix for the simplified cognitive map was calculated by combining the effects of the elements within the categories. This is done by applying Eq. (1) to each position in the matrix:

$$C_i = \frac{\sum E_j}{n}, \tag{1}$$

where C_i – weight for defined category; E_j – weight for element within category; n – summed number of elements.

Simplified individual cognitive maps based on defined categories can then be transformed into fuzzy cognitive maps. Condensing was performed for each individual cognitive map. When all individual maps are condensed and transformed into previously defined categories, they can be combined to obtain the overall cognitive map from all stakeholders. The data from the individual mental models were combined into the aggregated stakeholder matrix, taking into account that connections of opposite sign reduce causality and those of the same sign – increase it. A new matrix was created for each group on the basis of the aggregated data obtained for the factors and their connection strengths. Combined maps can provide information that cannot be captured by individual maps. An individual adjacency matrix of defined categories was used to obtain the combined cognitive map of the stakeholders. They are combined by applying Eq. (2) for each position in the matrix.

$$C_i^{sum} = \frac{\sum_1^m C_i}{m}, \tag{2}$$

where C_i^{sum} – combined weight of category; m – number of cognitive maps.

When merging numerous individual cognitive maps, cognitive graphs become overly complex and difficult to understand. The adjacency matrix for combined cognitive maps includes all connections and their weights between categories; however, when results are represented in the form of a visual graph, some form of cutoff criteria must be introduced to simplify the graph if there are too many connections between categories. In the graph, only the most relevant connections with the strongest weights are included. For the combined mental models developed from the cognitive maps obtained in the workshops, the following cutoff criteria were selected: For each category the cut-off criteria was set at 0.7 (−0.7 for negative weights) and limit of maximum of 5 connections was set. There is no consensus on specific cutoff criteria to be set in fuzzy cognitive mapping research since it highly depends on number of FCMs being analyzed and clustered. The cutoff was established by the authors to identify the most influential factors and create an integrated model. By setting specific cutoff values, the number of connections in the model was limited to a reasonable

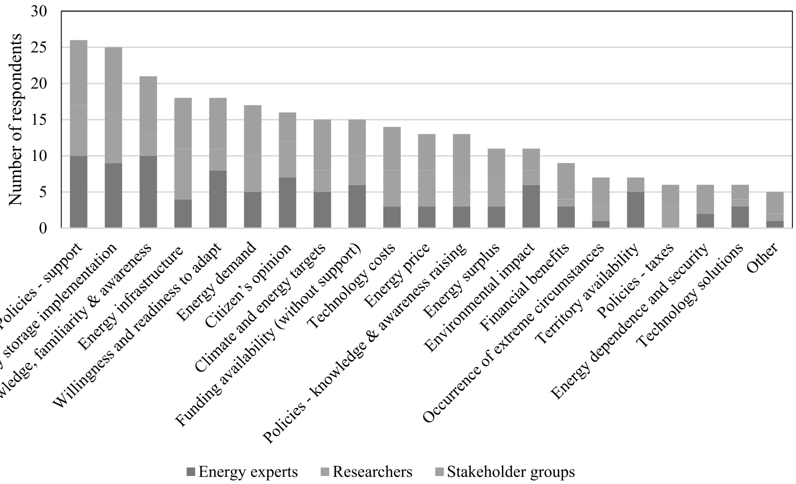


Fig. 3. Inclusion of the specific categories in individual models.

Table 3
Adjacency matrix of condensed mental models of all stakeholders.

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20
D1		0.24	0.50	0.24	-0.17	1.00	0.70		0.61		0.92		-0.33	-0.50	-0.37				-0.06	-0.10
D2	0.61			0.51		-0.46	0.56	0.42	0.33		0.56	0.41	0.27		0.60		0.52	0.31		
D3	0.66	0.64		0.07	0.80	1.00	-1.00	0.75			0.89	0.15	-0.14		0.59			0.34	1.00	
D4	0.67	0.79	0.04		-0.03		0.72	0.10	-0.03		0.50	1.00	0.69	-0.41	0.21	-0.20	1.00	0.58	0.03	-0.24
D5	0.53	0.82	-0.41	0.09		-0.36	-0.14	0.71	-1.00	-0.77			0.60	0.28	0.04	0.34	0.25			
D6	-0.57			-0.15	0.49		-0.90					1.00					-0.74			
D7	-0.08	1.00	0.46	0.30				0.68				-0.91					0.76			
D8	0.38	0.78	0.75	0.35	-0.33	-0.34	0.42		0.81	-0.37	0.53	0.52	0.61		0.62		0.66			0.33
D9	0.59	0.38	0.69	0.59	-1.00	-0.70		0.08		0.50	0.45	0.34		-1.00			-0.51		-0.57	
D10	0.72				-0.08	0.63			0.72							0.13				
D11	0.67	0.53	-0.02	0.46	-0.62	0.10	0.64	0.57	0.53			0.59	0.22		0.52		0.54	0.54	-0.43	
D12	0.60	0.49		0.10				0.42			0.78				0.45		0.43	0.29	-0.80	0.20
D13	0.73	0.55		0.46	-0.26			1.00			0.73			0.59						0.25
D14	-0.13																-0.41			
D15	0.63	0.81		0.74	-1.00	0.63			0.62		0.51	0.67	0.21	-0.39		-0.81	0.45	0.69		
D16	0.67	0.13		-1.00	0.63	-0.06		0.26	0.50		0.40		-0.65		-0.39		0.61			
D17	0.60	0.54		0.76		-1.00	0.50	0.46	0.71		-0.29	0.44	0.26		0.53			0.43		0.54
D18	0.61		-0.45	0.60	-0.17	-0.42	0.60						-0.53				0.24		-0.68	
D18	0.59	0.53		-0.54					0.53	0.50	1.00						0.14			0.38
D19	0.45	0.43		0.63				0.56												

extent, ensuring a comprehensive perspective.

3.4. FCM factor analysis

To measure the strength of the impact of the factors outlined in the mental models, the centrality score was analyzed. Centrality is one of the parameters used to analyse the combined mental models of different parties. The weight of a factor can be determined by calculating its centrality index. It shows the extent to which a given factor is important or central in the context of other factors and also reflects the cumulative strength of connections with other factors. The higher the value of the centrality index, the greater is the individual weight of the factor in the model. 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 scores were compared to examine how some factors performed in relation to others. Centrality was calculated by combining the indegree and outdegree values of the adjacency matrix.

4. Results and discussion

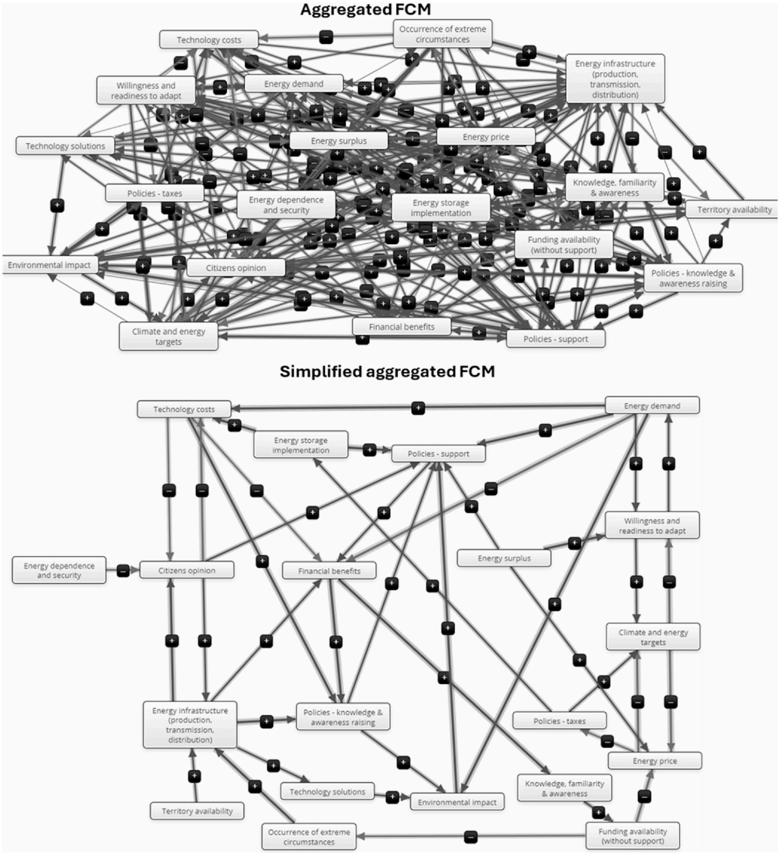
4.1. Key parameters and differences of FCM between stakeholder groups

The results revealed significant differences in the mental models developed by the energy experts, researchers, and stakeholder groups. A summary of the key parameters of mental models by main participant segments is outlined in Table 1. Examples of mental models of different stakeholders are illustrated in Fig. 2, which is intended to illustrate the differences in the complexity of the models between the various stakeholders based on their field of activity.

A total of 16 models from the first workshop were found to be valid and used in the analysis (combining the mental models of 9 energy experts and 7 researchers). The results of the first workshop showed that there was a large difference of developed individual mental models between energy experts and researchers. On average, energy experts included almost 10 more factors than researchers and, on average, made 14 more connections. On average, energy experts defined more factors and made more connections; however, researchers made more connections per defined factor. The number of factors included in the energy experts' models ranged from 12 to 40. The average number of factors for all models was 25. The number of connections included in the energy expert models ranged from 20 to 74, with an average of 44. The number of factors included in the researchers' models ranged from 12 to 20. The average number of factors for all models was 15. The number of connections included in the researchers' models ranged from 22 to 43, with an average of 29.

A total of 10 models from the second workshop were found to be valid and used in the analysis. The number of factors and connections in the participant models from the second workshop were fewer than those in the models created by energy experts and researchers in the first workshop. The connections for each defined factor were slightly smaller, but the difference was not significant.

Differences in decision making and perceptions of municipal energy infrastructure and policy were observed in the mental models of different stakeholder groups (Fig. 2). Municipalities focus more on the identification of local needs, highlighting the role of citizens' opinions and the availability of technological solutions that would specifically address local [47]. Whereas energy experts have highlighted the technical aspects and nationally binding climate and energy targets that



Aggregated FCM

Simplified aggregated FCM

Fig. 4. Aggregated FCM of all stakeholders.

drive local energy transitions [48]. However, energy experts may rely on theoretical studies and data analysis for efficient implementation of energy decarbonization strategies [48]. Researchers' mental models were primarily focused on political factors, viewing policies and governmental actions as the main drivers of local energy transitions. These mental models are more focused on external factors such as political and price considerations, rather than internal challenges.

4.2. Combined results of FCMs

After receiving all the individual models, they were standardized, categorized, condensed, and combined based on the methodological approach described above. In total, 458 factors were mentioned in the mental model maps, and 266 of the factors were identified as unique. The first step before combining the models was standardization and categorization to reduce information clutter. Factors similar to those mentioned in the individual models were combined and categorized. In total 21 categories were defined and are outlined in Table 2. In Appendix 1, all factors mentioned in the individual models are listed under a specific category.

Fig. 3 outlines the frequency of each category mentioned by each group of workshop participants. The majority of respondents emphasised the significance of energy storage implementation and support policies for energy storage deployment in municipalities. In contrast, tax policies, energy dependence and security, and technology solutions were only mentioned by a minority of respondents. Most energy experts and local energy transition stakeholder groups of the second workshop emphasised knowledge, familiarity, and awareness, while researchers mentioned these aspects significantly less. The same pattern is observed in the category concerning the willingness and readiness to adopt storage technologies. Most energy experts and local energy transition stakeholder groups of the second workshop consider it a crucial factor, while researchers mention it less frequently. The researchers did not discuss territory availability and energy dependence and security as factors affecting energy storage implementation. Additionally, the local energy transition stakeholder groups in the second workshop did not bring up tax policies. Energy experts are the only group that incorporates elements from all categories into their mental models. However, energy experts mentioned the category of territory availability less frequently.

The factors were categorized, and the individual models of the participants were then condensed and simplified. Factors in each model were substituted with corresponding categories outlined in Table 3. The mental model graphs were converted into an adjacency matrix and all the necessary recalculations were completed. Individual mental models were aggregated and combined to create the consolidated stakeholder mental model representation. Further, the analysis of mental model frameworks of three distinct groups – energy experts, researchers, and local energy transition stakeholders – both individually and collectively was performed.

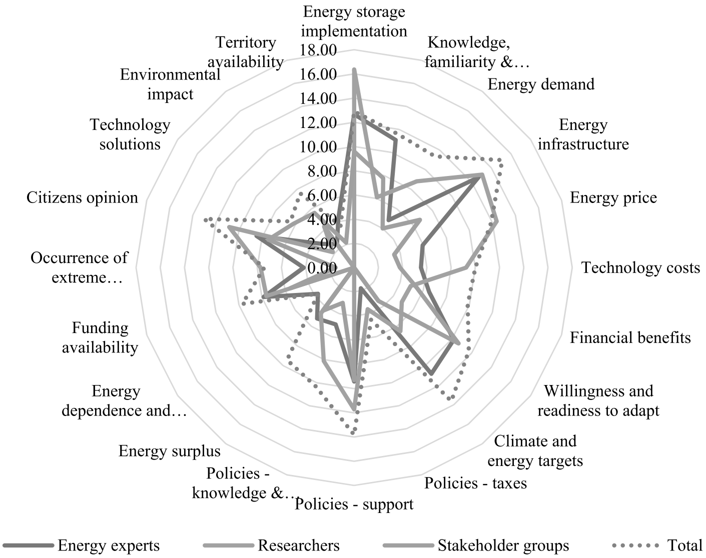


Fig. 5. Centrality profiles of defined categories.

Fig. 4 shows the condensed mental model of all workshop participants. It comprises 20 categories and 183 connections linking these categories. The graphical representation with all connections is difficult to understand, so the adjacency matrix (Table 3) is provided. An adjacency matrix can identify all connections with specific weights. There are numerous weak connections among factors identified by workshop participants, but the impact is minimal.

To enhance the clarity of the combined mental model, it is simplified by removing the least influential connections and retaining only the most robust connections among the specified categories. The cutoff criteria for simplification are described in the methodology section. Each category has the strongest links, with a minimum of one connection and a maximum of six connections. It should be noted that the cutoff criteria for each category were met before the maximum number of allowed connections was reached.

The simplified combined model consisted of 20 categories; however, the number of connections decreased from 183 to 41. Energy demand has the most outgoing connections (5), while the energy infrastructure has four outgoing connections. As these are the connections with the highest weights, it can be concluded that these two categories have a significant impact on the overall system and have a significant role in energy storage implementation. Support policies and financial benefits were the categories with the most incoming connections. Many connections have values of 1 and -1, which means the strongest possible connection between categories.

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. Centrality indicates the extent to which a given factor is important or central in the context of other factors and reflects the cumulative strength of connections with other factors. The higher the value of the centrality index, the greater the individual weight of the factor in the model. In general, a higher centrality index value indicates the importance of a factor to other factors with which it is related.

Fig. 5 illustrates the centrality profile for each group – energy experts, researchers and local energy transition stakeholders. The centrality profiles for each group were different.

For energy experts, the most central categories were energy infrastructure and energy storage implementation, knowledge, familiarity & awareness, climate and energy targets, willingness and readiness to adapt. Similarly, also 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 & awareness, and citizens opinion.

Overall, it can be seen that 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, also energy experts acknowledged knowledge, familiarity & awareness as one of the most important factor influencing energy storage deployment in local energy infrastructures. However, researchers more emphasise energy price and support policies as the key driver for change.

When analysing the combined outcomes of mental models, energy infrastructure emerged as the most pivotal factor, followed by support policies, climate and energy targets, and citizens' opinions. Signaling that all four aspects of sustainability - technical, economic, environmental, and social factors are considered equally important.

Categories such as energy dependence and insecurity, territorial availability and environmental impact were mentioned less frequently and therefore appeared to be the least central factors in the mental models of all the research groups in the study.

4.3. *Prospects for further application of FCM results*

The mental modeling workshop provided valuable information on the most important aspects affecting the implementation of energy storage in municipalities. The obtained models made it possible to identify the main categories responsible for the use of energy accumulation and its implementation in municipal energy systems. Not only the factors affecting the implementation of energy storage were identified, Mental model

Causal loop diagram

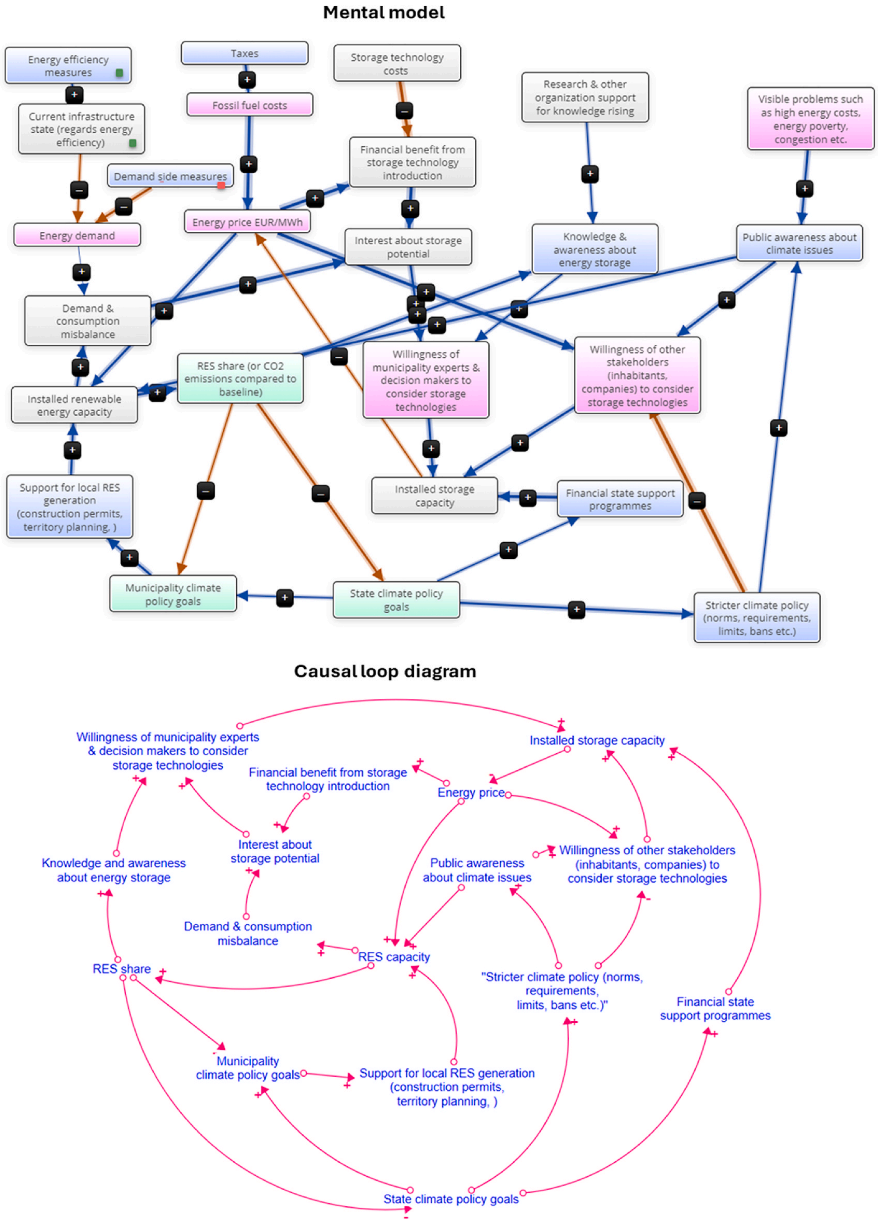


Fig. 6. Mental model conversion to feedback loops.

but also the relationships between them were determined, as well as the weights for the identified relationships were determined.

A better understanding of the linkages between different municipal energy system components serves as valuable input for further results application in system dynamics model development. System thinking and system dynamics modelling are related to causalities, feedbacks, and closed loops. System thinking theory states that the system itself is responsible for its behavior, not for some external force; therefore, it is crucial to understand what the elements of the system are, how they are connected, what the causes are, and what the effects are. A part of system thinking is closed-loop thinking. Closed-loop approach perceives causality as an ongoing process, instead of a one-time event, and it recognizes that the effect most often feeds back to influence the causes, and causes affect each other. Feedback loops are part of every system. To understand the system and its behavior, it is important to recognize the feedback loops in the system. Individual mental models obtained in workshops can be analyzed, and feedback loops can be searched within them to gain additional knowledge about the system or the perception of the system from various participants. The analysis of feedback loops from individual models could be the next step in the research.

The mental modelling workshops in this study have helped to identify the key feedback loops of factors influencing the energy transition in the municipal energy system. Fig. 6 depicts an example of one of the primary feedback loops identified in the mental model developed by workshop participants. A total of nine feedback loops were identified in the specific mental model.

Feedback loops reveal various interconnections between the factors. The higher the municipal climate goal ambitions, the more facilitated process (construction permits, territory planning) for RES capacity increase in the region. High initial renewable energy shares, however, diminish the overall ambition of climate policy. Municipalities can anticipate greater support for the deployment of RES as national energy policies become more stringent. By driving stricter regulations, national objectives increase awareness of RES and energy storage. In tandem with national objectives, financial support programmes expand, which increases storage capacities and decreases energy costs. Increased energy costs stimulate stakeholder interest in storage, which reduces costs and expands the share of renewable energy. The demand-consumption misalignment increases interest renewable energy capacity expansion, which stimulates interest in storage solutions.

5. Conclusions

Fuzzy cognitive mapping is an effective tool in understanding perceptions of different stakeholder groups which are crucial in effective policy making, particularly in the context of energy storage deployment in local energy systems. This study identifies and outlines the key drivers of energy storage deployment in municipal energy infrastructure identified by different groups of stakeholders. Often policy makers have different perspectives from the primary actors responsible for implementing and adapting to new policies. Therefore, it is important to consider different perceptions of main stakeholders of local energy transitions to facilitate communication and develop more effective energy policies.

While factors vary, support schemes such as subsidies, knowledge and awareness raising campaigns emerge as a central focus across stakeholder groups. Differences in decision-making and perceptions are evident, with municipalities emphasizing local needs, citizens' opinions and the availability of technological solutions that would specifically address local concerns while energy experts prioritize role of technical aspects and national climate policies. Municipalities addresses 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.

Fuzzy cognitive mapping is a valuable instrument that can facilitate the identification of feedback loops and the conceptualization of the local energy system's structure of dynamics. Mental model integration into system dynamics modelling, allows to better understand how different system actors perceive causal interconnection, delays and influences within a system [49]. Mental model integration enables a development of more comprehensive of system behaviour by helping to investigate potential unintended consequences resulting from feedback loops [50].

Fuzzy cognitive mapping methodology enables the identification of potential latent interdependencies in system behaviour that may be imperceptible through formal analysis [50]. In-depth analysis of the mental models of key stakeholders can help to design tailored energy policies and instruments for better decision-making in the field of local energy transition.

CRediT authorship contribution statement

Kristiana Dolge: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Armands Gravelsins:** Methodology, Formal analysis, Data curation. **Laura Kristiana Vicmane:** Writing – original draft. **Andra Blumberga:** Validation, Methodology, Conceptualization. **Dagnija Blumberga:** Validation, Project administration, Conceptualization.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix 1. Factors included in the categories

D1 - Energy storage implementation				
Energy storage capacity	Energy storage equipment	Energy storage implementation	Factors affecting energy storage	Investments in storage system
D2 - Knowledge, familiarity & awareness				
Knowledge & awareness about energy storage	Higher education (engineering) among municipal employees	Education and science	Media & newspapers	Technical support & specialists
Interest about storage potential	Unsuccessful energy storage projects	Examples of realised storage projects local or abroad	Forerunner role model	Technical knowledge of the staff in municipality

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Public awareness about climate issues	Number of good graduates in the field of energy	Legal and planning representatives' knowledge on energy storage	General understanding of the energy transition	Energy auditor
D3 - Energy demand				
Energy demand	Production (industry)	Local factories, workplaces	Building energy efficiency	Location/size of municipality
Current infrastructure state (regards energy efficiency)	Energy losses	Citizen's income level	Number of parties involved in the energy sector	Population
Energy consumption	Amount of energy to be stored	Peak demand		
D4 - Energy infrastructure (production, transmission, distribution)				
Installed renewable energy capacity	Energy production from controllable resources	Energy sent to the grid	DH system state - readiness to add components	Energy availability
Energy production	Energy production from fossil fuels	RES share increase	Potential waste energy	Technical state of the system
Energy share from RES	Energy production from variable RES	Energy producers	Local RES energy capacity	Technologies to be implemented
Type of energy and technology	Investment in variable RES	Proximity of the municipality to different energy sources (fossil based)	Recovered waste energy	Location of existing transmission networks
Suitable RES technology	Available grid capacity	Potential local RES energy	Renewable energy infrastructure development	Existing energy infrastructure
D5 - Energy price				
Energy price	Energy production costs	Cost of energy	Energy tariff	Energy price variation
Visible problems such as high energy costs, energy poverty, congestion etc.	Energy transmission costs	The price for the electricity transferred to the network	Renewable energy price	Transmission costs
D6 - Technology costs				
Storage technology costs	Cost of RES technology	RES investment cost	Equipment costs	Implementation costs
Capital investments in storage technologies	Investment	Price of technology	Installation costs	
D7 - Financial benefits				
Financial benefit from storage technology introduction	Income for the energy transferred to the network	The economic feasibility of the solution	Life cycle for equipment	Less bills
Payback time	Economic use for citizens	Better living	Profit	
D8 - Willingness and readiness to adapt				
Willingness of municipality experts & decision makers to consider storage technologies	Willingness of other stakeholders (inhabitants, companies) to consider storage technologies	Political willingness of municipal authorities & authorities (plans for development)	Outside stakeholders interested in joining the system as energy storage providers	Long term investment (+10 y pay back) and politics (4y. cycle)
Technical action	Sustainable politics	Available resources: technological and human	Lack of time and mental/ emotional resources	Decision making
Political will	More jobs	Municipal employees' interest in innovations	Dialogue with stakeholders	Participation
Amount of people that are PRO RES & storage technologies	Municipal employee capacity	Society interest in energy projects as solution for reducing impact on climate	The authority representing the local government	Administration
D9 - Climate and energy targets				
Municipality climate policy goals and environmental ambitions	National legislation on mandatory climate goals in municipalities	Environmental policy	Stricter climate policy (norms, restrictions, requirements, legal obligations limits, bans etc.)	The ability of municipalities to influence energy decisions
State climate policy goals	National legislation on energy independence	National requirement for energy storage (RES)	Prioritized energy storage issue or smart energy systems	Zero emission zones
D10 - Policies - taxes				
Taxes and fees	Shifting tax incentives from fossil fuels to RES	Tax relief	CO_2 tax	
D11 - Policies - support				
Demand side measures	Support research	Partial coverage of production costs	NET metering/billing system	Salaries for teachers
Support for local RES generation (construction permits, territory planning)	100 % support	Other financial incentives	Fluctuation mitigation measures	Municipality investments in R&D
Energy efficiency measures	Some other form of compensation/assistance/support	EU funding for energy storage	The requirement to ensure price stability	Legislative framework & regulations
State financial support	Support for technology transfer	Simplified legislation	Subsidies for installation/ purchase/maintenance of equipment	The ease of interaction with the municipality
Reducing bureaucracy	Attracting projects and funds from the country and abroad	National support schemes	Investments	Easy accessible financial support
Standards and requirements	Municipality involvement in governmental decisions	Municipal regulations		
D12 - Policies - knowledge & awareness raising				
Research & other organization support for knowledge rising	Funding for information campaign in favor to storage	Staff qualification improvement	Raising motivation	Cooperation with scientists
Information and awareness raising campaigns	Mobility and knowledge share with experts local or abroad	Dissemination of information	Educating the population	Seminars
Science and R&D funding	Economic feasibility study	Higher education preparing specialists on smart energy systems	Educational materials	Projects

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Number of students enrolling in applied fields	Evaluation of the technical system	School reforms to make pupils more interested in applied sciences	Cross municipality training projects	
D13 - Energy surplus				
Demand & consumption misbalance	Energy surplus	Availability of storable energy	Developed RES to form the demand for storage systems	Variable/intermittent energy production in RES
D14 - Energy dependence and security				
Energy dependence	State security	Security of energy supply	Energy poverty	Energy stability
D15 - Funding availability (without support)				
Available financial resources	High share of tax evaders	Private investment	Income level of citizens’	Financial situation
Economic situation	Health and education budget	Overall welfare of the municipality/free cash flow	Municipalities budget allocated to the smart energy systems	Other priorities
D16 - Occurrence of extreme circumstances				
High vulnerability to power shortages in the region: a need to secure energy sources	Local and international conflicts	Climate crisis	Power outages	Climate change
National spending for covering extreme weather cost	Force major	Extreme weather instances	Occurrence of unforeseen events	
D17 - Citizen’s opinion				
Demand from voters	Voter’s decision	Consent of landowners	Public attitude	Residents’ satisfaction with the work of the municipality
Citizen’s opinion and satisfaction	Society	Popularity of RES and energy storage in public eyes	Support from local community to implement innovations	The readiness of residents of building inhabitants to lease their land for storage
D18 - Technology solutions				
Demand side management possibility	Available storage facilities	Technical solutions	Technology availability	Sector coupling
Technology development	Available technologies	Inventions vs. innovations	Restrictions on the transmission of electricity to the network	
D19 - Environmental impact				
Environmental benefits	Environmental parameters	Improved environment	GHG emissions	Reduction of CO2 emissions
Disturbances in ecosystems	Attractive work environment, emission reduction in energy production	Local emissions and air pollution	Particulate matter emissions	Nature
D20 - Territory availability				
Available land for storage	Spatial planning and availability for RES	Geographical conditions	Lease governmental properties’ land	Environmental and legal availability to build new power infrastructure
D21 - Other				
Mental support for students	Market capacity	State in raw material supply chain for technology production	Social conditions in the municipality	Social factors

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PAPER 10: ECONOMIC GROWTH IN CONTRAST TO GHG EMISSION REDUCTION MEASURES IN GREEN DEAL CONTEXT.

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Original Articles

Economic growth in contrast to GHG emission reduction measures in Green Deal context

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ABSTRACT

The global economy is on the verge of one of the greatest transitions in modern history. The ability to ensure sustainable economic development and prosperity while significantly reducing consumption of energy resources and generated greenhouse gas emissions is a global challenge that affects every country in the world. To assess whether economies are ready for this challenge, there is an urgent need to examine this dual relationship between economic growth and climate change measures. European Green Deal strategy has set the ambitious goal of Europe becoming the first climate-neutral continent by 2050, boosting competitiveness and long-term prosperity of the economy. Kaya identity and LMDI decomposition is applied to examine how European Union countries have been coping with these countereffects historically. The decomposition analysis is conducted for the EU-28 (including the UK) countries for a 10-year study period from 2010 to 2019. This study analyses the main drivers of changes in GHG emissions in European Union and estimates the progress made in implementing the Green Deal targets. The results show that in the EU, energy efficiency improvements have twice the effect on reducing GHG emission compared to RES strategies. The effect of economic growth was the main offsetting factor hindering the achievement of larger GHG emission reductions. More in-depth ex-ante and ex-post investigation is performed for the Baltic States. A novel forecasting technique is applied to project GHG emissions under three different development scenarios, such as the scenario with existing measures, the scenario with additional measures, and the business-as-usual scenario. The results show that the current climate policies in the Baltic States are not sufficient to achieve the 2030 emission reduction targets and that greater efforts should be made to enforce climate mitigation measures in the economies.

1. Introduction

A 2020 Emissions Gap Report from United Nations Environment Program estimates that current nationally determined contributions (NDCs) are insufficient to meet climate change targets set at Paris Agreement. In fact, the latest projections show that existing national commitments will increase global warming by more than 3 °C by the end of the 21st century (United Nations Environment Programme, 2020). It signals that the current pace of progress in mitigating climate change is not fast enough to achieve the ambitious targets.

Collective procrastination and avoidance in the past requires greater efforts at the national level to achieve deep GHG emission reductions in the future. It is estimated that to meet the targets of Paris Agreement, the amount of emissions should decrease by at least 7.6% per year from 2020 to 2030 (United Nations Environment Programme, 2019). Furthermore, an IPCC Special Report on Global Warming of 1.5 °C (SR15) predicts that global greenhouse gas emissions must be reduced by at least 50% of current levels by 2050 to ensure a 50–66% probability of limiting global warming to 1.5 °C and achieving net-zero greenhouse gas (GHG) emissions (IPCC, 2018; Mastini et al., 2021). Any delay in reducing emissions will require even more serious and costly measures in the future and could entail serious institutional, socio-economic, infrastructural and structural risks (United Nations Environment Programme, 2019).

To raise the urgency and narrow the identified emission gap, the European Green Deal has set ambitious net-zero emissions targets by 2050. This commitment implies reducing GHG emissions by at least 55% by 2030, compared to 1990 levels (European Commission, 2020b). To reach the collective target, each EU member state is responsible for making a major contribution to achieving greater GHG emission reductions. Green Deal strategy has set the goal of European Union becoming the first climate neutral continent by 2050 by combining

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ambitious climate action with economic growth and prosperity enhancement (European Commission, 2020a). The complexity of this dual relationship between climate change measures and economic growth puts additional pressure on member states that need to lead the shift towards adaptation of sustainable economies. There is therefore an urgent need to examine how EU countries have dealt with these counter-effects in the past, and what the main drivers of change in GHG emissions are. Furthermore, in order to assess what progress has been made in implementing the Green Deal targets, it is essential to construct scientific projections of the future development of GHG emissions.

Since the European Commission announced its ambitious goal of achieving climate neutrality by 2050, a number of scientific publications and assessment reports have been published with extensive research on GHG emission trends and future trajectories in EU member states (Bianco et al., 2019; Brodny and Tutak, 2021; Hafner and Paolo, 2020). For example, in its most recent assessment report, the EEA estimates efforts to decarbonize and improve energy efficiency may not be sufficient to meet Green Deal 2030 targets. The green transformation and the transition to sustainable economies should move at much faster growth rates to achieve the predetermined binding targets. For instance, to achieve the EU's 2030 emissions reduction target of 40% for the EU-27, member states will need to reduce their emissions by 86 $MtCO_2$ eq. per year (EEA, 2020).

Identifying the key factors driving changes in GHG levels is an important precondition for designing effective GHG emission reduction strategies and policy instruments (Wang et al., 2019b). There is no consensus on a standardized model to estimate of GHG impact factors. Xie et al. (2021) use a novel robust reweighted multivariate grey model to simulate GHG emissions in the EU member states based on historical emission levels from 2010 to 2016. The findings reveal that emission intensity and primary energy consumption are the main determinants of GHG emission changes in all EU-28 countries. Therefore, the authors suggest that limiting total primary energy end-use and switching from fossil fuels to renewable energy sources are the two main directions with the greatest impact on GHG reduction targets in the EU (Xie et al., 2021).

Wang et al. (2019) argue that environmental problems escalate as economic growth increase, which is of particular concern to China and other developing countries in the world. The authors used the Kaya identity equation, Log-Mean Decomposition Index (LMDI), and Scenario Analysis model to explore the potential challenges related to China's roadmap towards dual-control 2030 CO_2 reduction targets. The results indicated that under the baseline scenario, China will succeed in reducing its CO_2 emission intensity and achieving the relative emission reduction targets, but it might not meet the targets of the "Paris commitments". The findings showed that economic development, energy intensity and energy mix have the greatest influence on the CO_2 reduction potential in China (Wang et al., 2019a). A paper by Tan and Wang (2021) states that increasing eco-efficiency will be the main driver for China to meet ambitious climate neutrality targets while maintaining competitive economic growth over the next decades as China has increased its carbon reduction targets. China expects to peak CO_2 emissions in 2030, which will be followed by a drastic reduction in carbon emissions until it reaches climate neutrality in 2060. The paper notes that the pace of innovation and growth of ecological efficiency in China will play a critical role in achieving a gradual reduction in carbon emissions generated per unit of GDP produced (Tan and Wang, 2021).

In energy policy research there have been several attempts to investigate the interlinkages of this dual relationship phenomenon using decomposition analysis techniques. For example, decomposition of Kaya identity indicators has been widely used in energy and climate policy studies to track progress towards goals set by international conventions and national governments (Kuriyama et al., 2019; Ortega-Ruiz et al., 2020; Štreimikienė and Balezentis, 2016; Tavakoli, 2018).

The Kaya identity is used to perform a decomposition analysis of the main driving forces of annual changes in GHG emissions. The Kaya equation links two contrasting narratives of climate change phenomena – decreases in emissions and energy intensity with long-term economic and population growth. Increasing economic activity and GDP growth creates more challenges and difficulties in meeting ambitious GHG emission reduction targets. A study by Mastini et al. (2021) outlines two converging narratives of development strategies for a sustainable low-carbon economy. Economic growth advocates arguing that economic growth is fundamental aspect and should be accelerated to ensure sufficient financing for large-scale investment projects for infrastructure and energy transition. In contrast, degrowth advocates stress that the scale of energy consumption must be significantly reduced at the cost of slowing economic growth to enable adaptation of a sustainable low-carbon economy (Mastini et al., 2021). The advantage of the Kaya identity is that it allows to identify whether current decarbonization and energy efficiency measures are large enough to offset the increase in GHG emissions due to the growing economy and population.

Decomposition analysis is used to unlock the explanation for the year-to-year changes in Kaya identity indicators. Decomposition analysis represents the changes in aggregate indicator by distributing the fluctuations through a number of predetermined impact components (Ang et al., 2003). The method is preferred as it can reveal the actual cause of changes in energy consumption and GHG emissions (Singpai and Dash, 2021).

A study by Lima et al. (2016) combines both the Kaya and LMDI approaches to perform a cross-country comparison of the main factors affecting changes in the amount of energy-related CO_2 emissions in Portugal, United Kingdom, Brazil and China. This group countries was deliberately to represent heterogeneities in the patterns of variation, which depend strongly on the different energy mixes and socio-economic backgrounds of the countries (Lima et al., 2016). Kaya identity with a combination of Shapley/Sun decomposition technique is used by Štreimikienė and Balezentis (2016) to investigate the changes in GHG emissions per capita in the Baltic States for the period from 2005 to 2012. The results showed that the reduction of energy intensity is a main factor for the reduction of GHG s in the Baltic States and that more emphasis should be placed on improving energy efficiency measures (Štreimikienė and Balezentis, 2016).

Some researchers use extended the Kaya identity in combination with decomposition analysis to examine the drivers of energy-related emissions, by using more specific variables that characterize national energy mix and structure (Apeaning, 2021; Bianco et al., 2019; Cicea et al., 2014; Kim et al., 2020; Mahony, 2013). For example, a study on Ireland's carbon emission changes by (Mahony, 2013) uses the extended Kaya identity model in combination with the Log Mean Divisia Index (LMDI), which integrates six different predefined decomposition factors, such as the effect of emission factor, the effect of fossil fuel substitution, the effect of energy intensity, the effect of renewable energy penetration, the effect of affluence, and the effect of population growth (Mahony, 2013).

LMDI decomposition analysis is used not only for cross-country comparisons, but also for cross-sectoral comparisons and sector-specific studies (transport, industry, services, agriculture, household sectors). Since the transport sector is one of the largest contributors to global GHG emissions, accounting for one-fourth of total GHG emissions, the study of the major GHG change components of the transport sector is of great importance (Nocera and Cavallaro, 2017). A study by Liu et al. (2021) combines the LMDI decomposition with the C-D production function to examine the relationship between economic growth factors and carbon emissions in the transport sector. Changes in carbon emissions of China's transport sector are decoupled from seven key factors such as emission intensity, structural, energy intensity, transport intensity, technology development, capital and labour input factors. The results show that energy structure and economic growth are the main accelerators of the increase in carbon emissions from the transport sector (Liu et al., 2021). Different study applies LMDI decomposition techniques to measure changes in energy consumption of industrial subsectors and concludes that the effect of industrial activity, which represent the effect of economic growth, is the main driver of changes in the amounts of energy consumed among all the factors considered, including the energy intensity effect and the structural effect (Dolge et al., 2021).

Although Kaya identity decomposition has been widely used by scientists both nationally and internationally, few studies have been conducted to analyze progress in reducing greenhouse gas emissions in the European Union. Especially in the last decade when the promotion of climate change action in the region became more essential. The novelty of this work lies in three fundamental dimensions of the research such as the method, the approach and the geographical application. First, the model developed involves both an in-depth analysis of historical data and the application of forecasting techniques. Consequently, conclusions are drawn not only from historical analysis but also from forecasting results. The scope of existing Kaya identity research is limited to the analysis of historical data with no attempts to use projections to predict GHG emission patterns in the EU. This study aims to fill this research gap by applying Kaya identity and LMDI decomposition to identify the main drivers of GHG emission changes in the European Union and estimate the progress made towards implementation of the Green Deal targets. Based on the decomposition analysis more accurate future development trajectories can be projected. The model developed in this paper could be applied by governments, local authorities, municipalities, regulators to monitor trends and progress in meeting regulatory requirements. The practical application of the model allows identifying and highlighting the most critical aspects in energy consumption ad carbon reduction patterns that should be taken into account to promote energy efficiency and decarbonisation adaptation. The results could be used by policy makers to shape more constructive and effective future energy and climate policies. Second, the research uses multidisciplinary approach by considering political, economic, technical and social aspects together. Therefore, the obtained findings could be utilized to improve performance and efficiency in all dimensions of long-term sustainability.

Third, to the authors' knowledge, no such research has yet been conducted in the Baltic States. In the second part of the study, the annual changes in GHG emissions in the Baltic States are examined in more detail. The decomposition analysis model is extended, and a scenario forecast is produced for Latvia, Lithuania and Estonia to assess whether current climate policies are sufficient to achieve the 2030 emission reduction targets set out in the NECPs.

The study includes both ex-post and ex-ante analyses to track progress towards climate change mitigation goals. Therefore, it demonstrates the application of novel assessment tool that could be used by policy makers to obtain a sufficient assessment of GHG emission trends and future patterns at both national and international levels.

2. Methods and data

A paper by Ang (2004) describes the most common methods of index decomposition analysis (IDA) and presents an algorithm for selecting the most desirable and appropriate IDA method. Two main groups of IDA methods can be distinguished: methods related to (1) the Laspeyres index and (2) the Divisia index. Both methods are further divided by their decomposition structure of the measured indicator aggregate change into either additive (difference change) or multiplicative (ratio change) decompositions. As a result, a total of eight different decomposition methods are reviewed and compared (Ang, 2004).

The main difference between the Divisia and Laspeyres index decomposition methods appears in the applied measurement of the underlying function and the interpretation of the result. The fundamental assumption behind the Laspeyres index approach measures the change in one variable and its effect over time by keeping other factors fixed at their base year values. The Divisia index uses the growth rates of the variables, expressed in logarithmic changes, as weights in calculating indicator changes. The Laspeyres index decomposition opens up possibilities for a simpler and more comprehensive interpretation of the results. While Divisia index decomposition is more explanatory and scientific compared to Laspeyres index decomposition (Ang, 2004).

Divisia index decomposition provides to choose between log mean function and arithmetic mean function techniques. Log mean Divisia index (LMDI) method is considered to be more advantageous compared to arithmetic mean Divisia index (AMDI) since it provides perfect decomposition and does not contain any undesirable residuals. On the other hand, AMDI methods might produce large unexplained residual terms, especially in cross-country comparison studies and large period time series analysis (Ang, 2004).

Laspeyres index decomposition method is not as simple as the Divisia index decomposition. The Laspeyres multiplicative approach includes conventional and modified Fisher ideal index methods, while the additive approach offers the Shapley/Sun method and the Marshall-Edgeworth method. Both the modified Fisher ideal index and the Shapley/Sun method are recommended in studies that do not contain more than three factors, since increasing the number of factors results in greater complexity of result interpretation and method application (Ang, 2004). The advantage of LMDI, Fisher ideal and Shapley/Sun decomposition analysis is that it allows to obtain decomposed values without unexplained residuals and thus to obtain a perfect decomposition (Ang et al., 2003).

This study applies Logarithmic mean Divisia index (LMDI) decomposition method to examine the main drivers of change in greenhouse gas emissions. The analysis is conducted for a 10-year period from 2010 to 2019 for the EU-28 countries (including the UK). The additive LMDI method is used due to its strong theoretical foundation and complete elimination of error terms, resulting in a perfect decomposition.

A naive approach to examining how changes in GHG emissions are affected by variations in population size, economic growth, energy consumption and emissions intensity is to construct a decomposition of GHG emissions into four main components of the Kaya identity: emissions intensity, energy intensity, GDP growth, population growth. The Kaya identity links GHG emissions to these components according to Eq. (1).

$$GHG_t = \frac{GHG_t}{E_t} \bullet \frac{\mathrm{E_t}}{\mathrm{GDP_t}} \bullet \frac{\mathrm{GDP_t}}{\mathrm{P_t}} \bullet \mathrm{P_t} \tag{1}$$

where $\mathrm{GHG_t}$ are greenhouse gas emissions in certain period, $\mathrm{E_t}$ is energy consumption in period, $\mathrm{GDP_t}$ is gross domestic product in the period, $\mathrm{P_t}$ is population in the period. Data for Kaya identity decomposition is collected form Eurostat database as summarized in Table 1.

The main goal of decomposition analysis is to identify the fundamental drivers that influence changes in historical data. A comprehensive assessment of each component's relative weight on GHG changes over time allows to determine the impact of certain renewable energy and energy efficiency policy measures (Albrecht et al., 2002). The changes in GHG emissions are determined by individual changes in each Kaya identity indicator, as represented in Eq. (2).

Table 1
Data sources for index decomposition analysis (Eurostat, n.d.-a, n.d.-b, n.d.-c, 2020).

Notation	Data	Data source	Data code
$\mathrm{GHG_t}$	GHG emissions in $\mathrm{tCO_2}$ eq (Total emissions as reported to international conventions (UNFCCC and CLRTAP))	Eurostat	[env_ac_aibrid_r2]
$\mathrm{E_t}$	Gross inland energy consumption in toe	Eurostat	[nrg_bal_c]
$\mathrm{GDP_t}$	GDP in MEUR (chain-linked volumes, base year 2015)	Eurostat	[nama_10_gdp]
$\mathrm{P_t}$	Population on 1 January	Eurostat	[demo_pjan]

$$\begin{aligned}\Delta(GHG)t &= \Delta(Emission\ intensity)t + \Delta(Energy\ intensity)t\\ &\quad + \Delta(GDP\ growth)t + \Delta(Population\ growth)t\\ &= \Delta\left(\frac{GHG_t}{E_t}\right)t\bullet\Delta\left(\frac{\mathrm{E_t}}{\mathrm{GDP_t}}\right)\mathrm{t}\bullet\Delta\left(\frac{\mathrm{GDP_t}}{\mathrm{P_t}}\right)\mathrm{t}\bullet\Delta\mathrm{P_t}\end{aligned} \tag{2}$$

Further Log-Mean Divisia Index (LMDI) decomposition method for a four-factor case is applied. The aggregate indicator of interest in this study is GHG emissions (denoted as *GHG*) which is determined by four pre-defined factors: emission intensity (denoted as EMI), energy intensity (denoted as *ENI*), GDP growth (denoted as *GDP*), and population growth (denoted as *POP*) where the following relationship between the variables holds true $GHG = EMI\bullet \mathrm{ENI}\bullet\mathrm{GDP}\bullet\mathrm{POP}$ Absolute change in the aggregate level of *V* between two different time periods from year *0* (base year) to year *T* is decomposed by absolute changes in each component, where $GHG^0 = EMI^0ENI^0GDP^0POP^0$ and $GHG^T = EMI^TENI^TGDP^TPOP^T$. From which it can be derived that $\Delta GHG = GHG^T - GHG^0 = EMI^TENI^TGDP^TPOP^T - EMI^0ENI^0GDP^0POP^0 = \Delta EMI + \Delta ENI + \Delta GDP + \Delta POP$(Ang et al., 2003).

According to LDMI I additive decomposition methodology, change in each component is determined by Eqs. (3)–(6).

$$\Delta EMI = \sum_i \frac{GHG^T - GHG^0}{lnGHG^T - lnGHG^0} ln\frac{EMI^T}{EMI^0} \tag{3}$$

$$\Delta ENI \sum_i \frac{GHG^T - GHG^0}{lnGHG^T - lnGHG^0} ln\frac{ENI^T}{ENI^0} \tag{4}$$

$$\Delta GDP = \sum_i \frac{GHG^T - GHG^0}{lnGHG^T - lnGHG^0} ln\frac{GDP^T}{GDP^0} \tag{5}$$

$$\Delta POP = \sum_i \frac{GHG^T - GHG^0}{lnGHG^T - lnGHG^0} ln\frac{POP^T}{POP^0} \tag{6}$$

where GHG is greenhouse gases, EMI is emission intensity, ENI is energy intensity, GDP is economic growth, POP is population size according to defined Kaya identity indicators in Eq. (2). Subscript 0 represents the values of base year, and subscript T represents future values. The same notation holds true for all the variables.

Based on Eqs. (3)–(6), the changes in GHG emissions can be calculated for the EU countries. The chosen time interval of the study covers the 10-year period from 2010 to 2019. The time interval is justified because the national energy and climate plans of the EU member states also cover a 10-year period. Therefore, progress can be reasonably assessed.

Since this study will additionally investigate how historical patterns in GHG emission changes can be used to project future trends in GHG emissions, the model is further extended. The expanded model includes the prediction of GHG emissions based on decomposition analysis. The following steps for calculating GHG projections are based on techniques shown in studies by Sadorsky, (2021) and Lin and Ahmad (2017).

If base year value of GHG emissions GHG^0 is known, GHG emissions for future year GHG^T can be forecasted using Eq. (7).

$$GHG^T = GHG^0 + \Delta EMI + \Delta ENI + \Delta GDP + \Delta POP \tag{7}$$

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. (8)–(11).

$$EMI^T = EMI^0\bullet(1+\alpha) \tag{8}$$

$$ENI^T = ENI^0\bullet(1+\beta) \tag{9}$$

$$GDP^T = GDP^0\bullet(1+\delta) \tag{10}$$

$$POP^T = POP^0\bullet(1+\varepsilon) \tag{11}$$

Following the fundamental basis of Kaya identity as demonstrated in Eq. (1) and coping it with Eqs. (8)–(11), forecasted GHG emissions can be obtained using Eq. (12).

$$GHG^T = GHG^0\bullet(1+\alpha)\bullet(1+\beta)\bullet(1+\delta)\bullet(1+\varepsilon) \tag{12}$$

Further Eq. (12) is put in Eq. (3) to obtain yields, we obtain relationship that is demonstrated in Eq. (13).

$$\Delta EMI = z\bullet(1+\alpha) \tag{13}$$

where

$$\mathrm{z} = \frac{GHG^0\bullet[(1+\alpha)\bullet(1+\beta)\bullet(1+\delta)\bullet(1+\varepsilon)-1]}{ln[(1+\alpha)\bullet(1+\beta)\bullet(1+\delta)\bullet(1+\varepsilon)-1]} \tag{14}$$

Same relationship holds true for other factors, as presented in Eqs. (15)–(17).

$$\Delta ENI = z\bullet(1+\beta) \tag{15}$$

$$\Delta GDP = z\bullet(1+\delta) \tag{16}$$

$$\Delta POP = z\bullet(1+\varepsilon) \tag{17}$$

To derive Eq. (18) that is used for GHG emissions forecasting, Eqs. (13)–(17) are further inserted into Eq. (7).

$$GHG^T = GHG^0 + z\bullet(1+\alpha) + \mathrm{z}\bullet(1+\beta) + \mathrm{z}\bullet(1+\delta) + \mathrm{z}\bullet(1+\varepsilon) \tag{18}$$

Future values of GHG emissions can be projected using Eq. (12) or (18) if growth rates are defined for each factor (EMI, ENI, GDP, POP). CAGRs are determined using an exponential smoothing forecast based on historical years from 2010 to 2019. The forecast is carried out for a period from 2020 to 2030. The predicted values are further used for scenario analysis (Sadorsky, 2021). The determined CAGRs are used to construct the Existing Measures scenario. The values from the upper 95% confidence interval of the forecasts are used to project the “Business as usual” scenario. In contrast, the numbers from the lower 95% confidence interval are used to construct the “Additional Measures” scenario. The key assumptions of the scenario analysis are shown in Table 2.

3. Results and discussion

3.1. LMDI decomposition results for EU-28 countries

The results for the EU-28 countries (including the UK) are shown in Fig. 1. 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.

Table 2
Description of forecast scenarios.

Scenario	Explanation	Values
Existing measures	Baseline scenario if current trends in GHG emission factors continue at the same historical levelized growth rate	Base values
Additional measures	Green growth scenario if current climate change measures are supplemented with stronger instruments to achieve larger GHG emission cuts	Lower 95% confidence bound values
Business as usual	No-climate-policy scenario if economic growth measures are boosted without consideration of sustainability aspects	Upper 95% confidence bound values

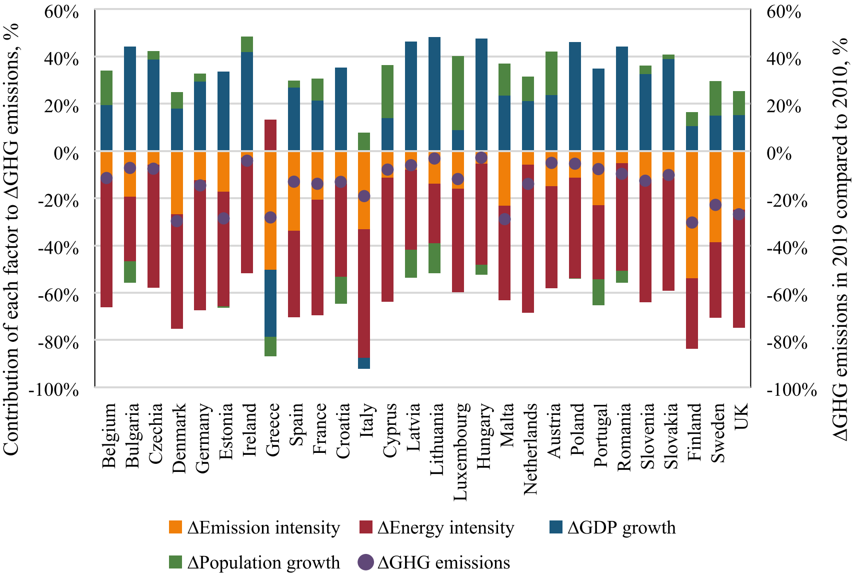

Fig. 1. Kaya identity decomposition for the EU-28 countries.

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.

The decomposition analysis reflects the main driving forces for changes in greenhouse gas emissions. Significant differences, but also similarities, can be identified between EU member states. For most countries, improving energy intensity was the largest contributor to GHG emission reductions, with an exceptionally high importance in countries such as Ireland and Hungary. Indeed, in the EU, the impact of changes in energy intensity had more than twice the impact on GHG emissions as changes in emissions intensity.

Energy intensity reductions were found to have the largest impact on GHG emission reductions in all Baltic States and in Denmark. In fact, energy efficiency measures were twice (in Denmark) or even four times (in Latvia) more effective than RES strategies. In contrast, in some countries such as Finland and Sweden, changes in emissions intensity had the largest effect on the change in GHG emissions. This can be explained by the fact that both countries showed remarkable improvements in decarbonisation during the period studied. The share of RES in 2019 increased by 10.8 percentage points in Finland and 9.8 percentage points in Sweden compared to 2010 levels.

Increasing economic activity, as measured by GDP growth, was the main offsetting factor preventing the achievement of larger reductions in GHG emissions for almost all countries except Greece and Italy. The effect of GDP growth was particularly high in Ireland and several Eastern European countries such as Lithuania, Latvia, Hungary and Poland, as these countries recorded the highest increase in GDP per capita during this period. On the other hand, both Greece and Italy experienced a decrease in GDP per capita, which contributed to a reduction in GHG emissions.

The population growth factor had a negative impact on the change in GHG emissions in the majority of countries, with the largest impacts observed in Luxembourg, Cyprus, Belgium, Austria and Sweden. However, in some countries (Baltic States, Portugal, Croatia, Bulgaria, Greece, Romania, Poland) the population decreased over the last decade, which had a positive impact on the decrease of GHG emissions. Despite the lower GDP growth, the population growth factor in the Nordic countries had a negative impact on the accelerated reduction of GHG emissions. In the Baltic countries, on the other hand, the decreasing population contributed positively to the achievement of larger GHG emission reductions.

In lower-income countries such as Latvia and Lithuania, GDP growth was the main driver of change in GHG emissions. Although significant improvements in energy and emissions intensity reductions were achieved during the 10-year period, the pace of reductions did not offset and compensate for the impact of increasing economic activity. Compared to the other Baltic States, Estonia stood out with greater progress in reducing energy and emissions intensity, which was able to offset increasing economic activity and achieve greater reductions in GHG emissions. The results show that countries with initially higher GHG emissions per capita in 2010, such as Finland and Estonia, have made greater progress in reducing GHG emissions over the past decade.

The results suggest that the case of Sweden can be used as a benchmark for achieving the highest impact on GHG emission reductions. Despite significant increases in GDP and population growth, equally high emphasis on both – carbon intensity reduction and energy intensity reduction – is necessary to create positive synergies and achieve higher cumulative GHG emission reductions.

3.2. *Year-to-year LMDI decomposition results for the Baltic states*

The Baltic States are among the lower income countries when GDP (in PPS) per capita is compared with other EU countries (Eurostat, 2019). Therefore, more emphasis is placed on stimulating long-term economic growth in these countries in order to achieve the increase in prosperity and reach the level of more developed countries. As a result, the Baltic states may face greater pressure to maintain this dual control relationship between climate change measures and economic growth stimulation. In order to investigate how the Baltic states deal with these counter-effects, a more in-depth analysis is conducted for Latvia, Lithuania and Estonia to observe the annual changes in Kaya identity factors and to analyze the short-term effects on GHG emissions.

Summary statistics of changes in Kaya identity indicators for the Baltic states are presented in Table 3. From the comparison of the main Kaya identity indicators, it can be seen that Latvia has the lowest emission intensity compared to the other Baltic States. However, Latvia showed the slowest progress in reducing emission intensity over a ten-year period. The energy intensity indicator is similar for all countries and is almost at the same level in 2019. Historically, Estonia has the highest GDP per capita, followed by Lithuania and Latvia, which have similar income levels. The highest population is observed in Lithuania, while the lowest is observed in Estonia. Both Latvia and Lithuania experienced a significant decrease in the total population, while no significant changes in the number of inhabitants were observed in Estonia during the period from 2010 to 2019.

LMDI decomposition results for selected countries are summarized in Table 4. In Latvia (Fig. 2.), 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.

Table 3
Summary statistics on changes in Kaya identity indicators for the Baltic States.

	2010	2019
GHG emissions ($MtCO_2$ eq)		
Latvia	12.28	11.54
Lithuania	20.89	20.22
Estonia	21.02	15.02
Emission intensity (GHG tCO_2eq per consumed energy toe)		
Latvia	2.65	2.48
Lithuania	2.95	2.59
Estonia	3.72	3.11
Energy intensity (Consumed energy toe per GDP MEUR)		
Latvia	0.23	0.17
Lithuania	0.23	0.18
Estonia	0.32	0.19
GDP growth (1000 EUR GDP per capita)		
Latvia	9.70	14.35
Lithuania	9.87	15.50
Estonia	13.23	18.71
Population (million inhabitants)		
Latvia	2.12	1.92
Lithuania	3.14	2.79
Estonia	1.33	1.32

Table 4
Results of the LMDI decomposition analysis for the Baltic States.

	Latvia	Lithuania	Estonia
ΔEmission intensity	−0.79	−2.66	−3.17
ΔEnergy intensity	−3.43	−4.88	−8.9
ΔGDP growth	4.66	9.27	6.18
ΔPopulation growth	−1.18	−2.41	−0.11
ΔGHG emissions	−0.74	−0.67	−6.00

Lithuania (Fig. 3) recorded the second lowest progress in the EU, where total GHG emissions fell by only 3.2% in 2019 compared to 2010. Improvements in energy efficiency (−4.91) and adaptation of renewable energy measures (−2.66) could not compensate for increasing economic activity (9.33) in this period, where a significant increase in GDP drove up GHG emissions. However, the decline in population growth (−2.43) during the period contributed to the modest cumulative GHG emission reduction results. Following the closure of the Ignalina nuclear power plant in 2009, the Lithuanian energy sector underwent significant restructuring. The decrease in primary energy production was largely replaced by fossil fuels and higher volumes of energy imports (Štreimikienė and Balezentis, 2016). Since 2010, Lithuania has made greater efforts to increase the share of renewable energy resources by increasing the capacity of wind turbines and promoting biofuels. However, the greater impact on the reduction of GHG emissions came from energy efficiency measures, which were more pronounced especially in the period from 2011 to 2013 and from 2018 to 2019, when energy intensity in Lithuania decreased significantly.

In Estonia (Fig. 4), the largest impact among Kaya identity decomposers was the decrease in energy intensity (−9.39). The overall changes in GHG emissions in Estonia on an annual basis showed much greater variability compared to the other Baltic States. The variability can be largely explained by the changes in the amounts of electricity generated from combustion fuels such as oil shale, which account for about 80% of the total primary generated energy in Estonia. In 2013 and 2017, when there was a record increase in electricity generation from combustible fuels in Estonia, total GHG emissions increased significantly in the representative years. Similarly, in 2015, when gross electricity generation from combustible fuels decreased by 20%, both emission intensity and total GHG emissions decreased significantly. Overall, Estonia showed the highest progress in reducing GHG emissions compared to the other Baltic States, achieving a reduction of 21.02 million tons of CO_2 equivalent or 29% in 2019 compared to 2010.

Although all three Baltic states have similar political and economic structure, geographical conditions and historical development background, the results of Kaya identity decomposition analysis reveal differences between Latvia, Lithuania and Estonia. The differences in the results can be explained by the significantly different energy production structures in each country. The Latvian energy generation sector has historically been more decarbonised compared to Lithuania and Estonia due to the high share of hydropower generation in the overall primary energy production balance. It is also represented in historically significantly higher share of renewable energy sources (see Table 6). As a result, in Latvia the LMDI factor of emission intensity contributed to changes in GHG emissions to the lower extent than it is observed for Lithuania and Estonia (see Table 4). As Lithuania and Estonia have higher untapped potential to improve emission intensity, this factor has a higher impact on GHG reduction targets compared to Latvia. Another difference between countries can be observed in the impact of the GDP growth factor on total GHG changes. The results show that for Latvia and Lithuania, which have lower income levels compared to Estonia, economic growth was the main factor driving GHG changes over the last decade. This indicates that policies in Latvia and Lithuania were aimed at achieving higher economic gains at the expense of lower environmental protection activity.

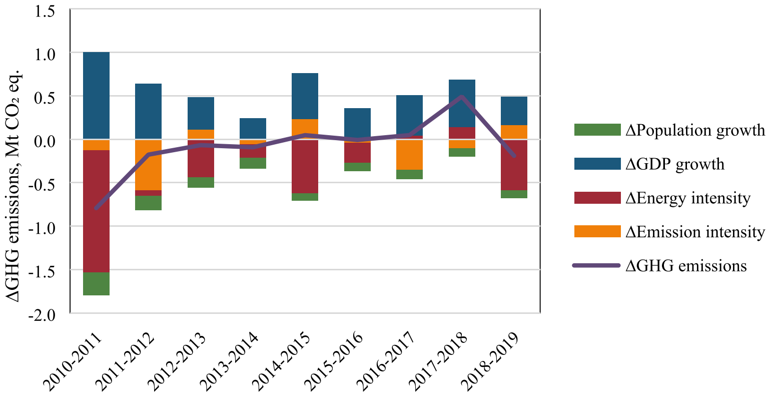

Fig. 2. Year-to-year Kaya identity decomposition for Latvia.

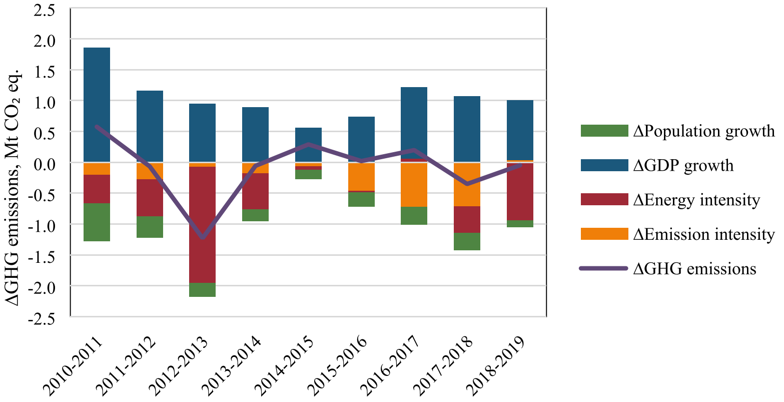

Fig. 3. Year-to-year Kaya identity decomposition for Lithuania.

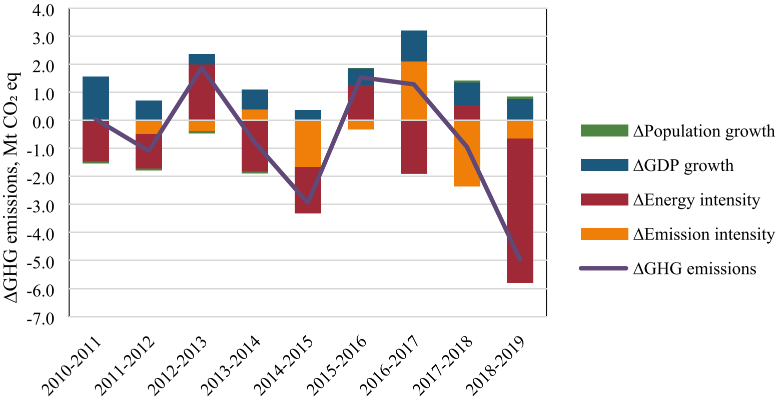

Fig. 4. Year-to-year Kaya identity decomposition for Estonia.

3.3. GHG emission forecasts for the Baltic states

The results of the LMDI decomposition analysis are further used to predict future trajectories for changes in GHG emissions in the Baltic states. The prediction is calculated following Eqs. (7)–(18). Three different scenarios are predicted for each country – the Existing Measures Scenario, the Additional Measures Scenario and the Business-as-Usual Scenario. The key assumptions and differences between the scenarios are summarized in Table 2. Table 5 summarizes the growth rates used for the Existing Measures baseline scenario.

The projected results of GHG emissions for Latvia, Lithuania and Estonia are shown in Fig. 5 to 7. Under the Existing Measures scenario, Latvia (Fig. 5) 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 (Cabinet of Ministers, 2020). 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.

The forecast results for Lithuania (Fig. 6.) show a decrease in GHG emissions in all three scenarios studied. If existing policies are continued, GHG emissions in Lithuania are projected to decrease by 6.4% in 2030 compared to 2019 levels, reaching 18.9 Mt CO_2 eq. Larger reductions in GHG emissions can be achieved by implementing additional measures. The projected values of the Additional Measures scenario for Lithuania show that the total GHG reduction potential for Lithuania corresponds to 10.4% reduction in GHG emissions by 2030 compared to 2019 levels.

Estonia has set a target to reduce greenhouse gas emissions by 70% by 2030 compared to 1990 emission levels. In absolute terms, Estonia plans to achieve 10.7–12.5 Mt of CO_2eq. GHG emissions by 2030, a 4.3–2.5% reduction in GHG emissions compared to 2019 levels (Estonia's Communication to the European Commission, 2019). The forecast results of this study indicate that Estonia will not meet its 2030 emission targets under the Existing Measures scenario, similar to what was observed in the case of Latvia (Fig. 7). The projected emission targets will only be met if additional measures are taken. Under the "Additional measures" scenario, the projected GHG emissions for Estonia will reach 10.1 Mt CO_2eq by 2030, which corresponds to Estonia's national emission target.

To move closer towards the achievement of EU's ambitious climate change targets, each Member State must develop a National Energy and Climate Plan (NECP). According to the rules of Regulation (EU) 2018/1999 on the governance of Energy Union and Climate Action, NECPs for the 10-year period from 2021 to 2030 were submitted by each member state to European Commission by the end of 2019 (European Parliament, 2018). Historical progress and national targets projected in the NECPs for the Baltic States are summarized in Table 6. Different target trajectories can be observed between countries.

When comparing energy efficiency targets for 2030, only Latvia and Estonia expect a decrease in absolute values of primary energy consumption compared to 2019 baseline values. Lithuania has foreseen an increase in primary energy consumption.

Lithuania expects primary energy consumption to increase by more than two-thirds in 2030 compared to 2019 estimates. The increase in energy consumption is expected to be offset by greater decarbonization efforts, as the share of RES is expected to increase from 26% in 2019 to 45% in 2030. The decomposition analysis on changes in Kaya identity factors showed that in the past energy efficiency measures were more successful in achieving GHG emission reductions in Lithuania. Considering the projected increase in the share of RES, the emission intensity in Lithuania is expected to decrease significantly in the next decade, which will change the current decomposition of the main GHG emission impact factors.

Table 5
CAGRs under "Existing Measures" forecast.

Country	EMI (α)	ENI (β)	GDP (γ)	POP (ε)
Latvia	−0.0069	−0.0190	0.0324	−0.0086
Lithuania	−0.0151	−0.0173	0.0413	−0.0138
Estonia	−0.0254	−0.0114	0.0285	−0.0010

As no progress in reducing primary energy consumption has been observed in Latvia, more emphasis is placed on improving energy efficiency in the next decade. Given the much higher share of RES in Latvia compared to Lithuania and Estonia, a modest decarbonization target for 2030 is foreseen for Latvia, signaling a higher importance of energy efficiency measures to promote GHG emission reductions.

Improvements in individual sectors, especially in households and transport sectors, which are the two largest energy consumers in the Baltic States, will play a crucial role in reducing GHG emissions in all countries analysed. While total household energy consumption has decreased significantly in all Baltic States over the last decade (2010–2019), total transport energy consumption has increased significantly in all three countries (Eurostat, n.d.-a). Moreover, the transport sector had one of the highest shares of total national CO_2 emissions in 2018, accounting for 64% in Lithuania, 46% in Latvia and 17% in Estonia (Enerdata, n.d.). This suggests that future climate policies targeting the transport sector will be one of the largest contributors to overall national GHG emission reduction targets.

Reducing energy consumption and emissions in these countries will be a particular challenge, as energy demand in the transport sector is highly dependent on economic growth factors and rise in overall economic prosperity. Both passenger and freight road transport require stringent policies aimed at increasing the energy efficiency of vehicles, decarbonising the fuel mix used and promoting alternative fuels, as well as encouraging a modal shift to public transport and reducing travel demand (Yan et al., 2021). All Baltic States foresee in their NECPs to increase the share of biofuels and reduce the energy intensity of the transport sector, leading to a significant reduction of national GHG emissions by 2030 (Cabinet of Ministers, 2020; Estonia's Communication to the European Commission, 2019; European Commission, 2021).

4. Conclusions

The Kaya identity and LMDI decomposition was applied to examine changes in GHG emissions due to changes in four predetermined factors such as emission intensity, energy intensity, economic growth and change in population size. The analysis is conducted for a 10-year period from 2010 to 2019 for the EU-28 countries (including the UK).

The results indicate that countries with initially higher GHG emissions per capita in 2010 show higher progress in reducing GHG emissions over the last decade. Rapidly growing economic activity in lower-income countries was the main offsetting factor hindering the achievement of larger reductions in GHG emissions. While significant improvements in energy and emissions intensity reductions were achieved over the 10-year period, the pace of reductions did not sufficiently offset and compensate for the impact of increasing economic activity. The results showed that over the 10-year period in the EU, the impact of energy intensity reductions had more than twice the impact on GHG emissions as emissions intensity reductions. In order to achieve greater reductions in greenhouse gas emissions, greater efforts should therefore be made to develop effective energy efficiency policies and to speed up the adaptation of energy efficiency measures in all sectors of the economy. The cross-country comparison of the Kaya identity decomposition analysis found that the case of Sweden can be used as a benchmark for achieving the highest impact on GHG emissions reductions. Despite significant increases in GDP and population growth, equal weighting of both – carbon intensity reduction and energy intensity reduction – is necessary to create positive synergies and achieve higher cumulative

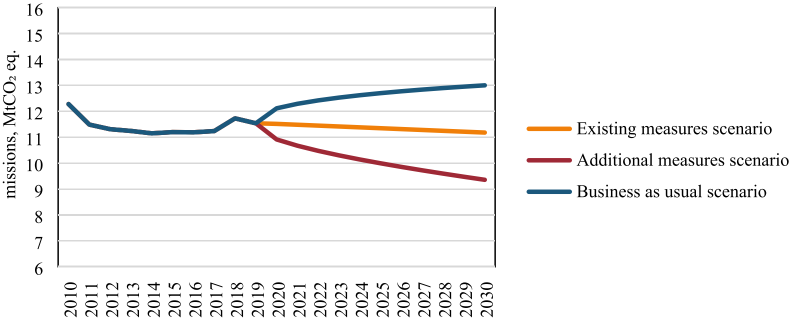

Fig. 5. Forecasts of GHG emissions for Latvia.

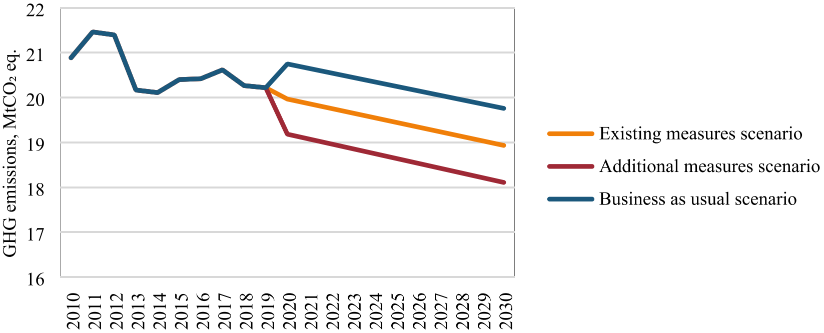

Fig. 6. Forecasts of GHG emissions for Lithuania.

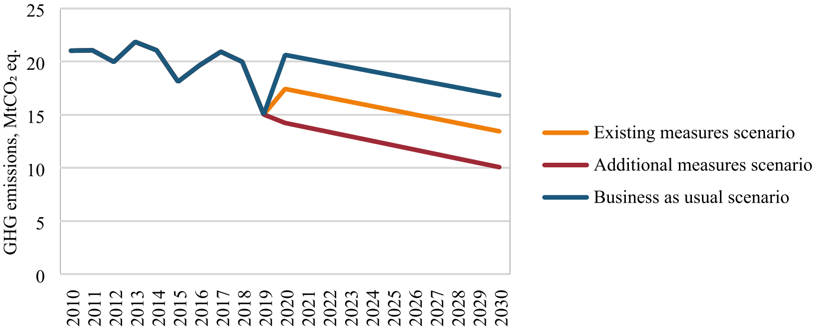

Fig. 7. Forecasts of GHG emissions for Estonia.

GHG emission reductions.

A more in-depth analysis, including both an ex-ante and ex-post assessment of GHG emissions, was conducted for the Baltic countries of Latvia, Lithuania and Estonia. These countries had one of the highest economic growth indices during the study period compared to other European Union countries. In addition, these countries have historically placed more emphasis on increasing economic growth and bringing their economies closer to the prosperity levels of more developed countries. Therefore, the Baltic States may face higher pressures to cope with the counter-effects and the dual relationship between climate change measures and the promotion of economic growth.

Forecast of GHG emissions for the Baltic States shows that current climate policies are not sufficient to achieve the 2030 GHG emission reduction targets set in the NECPs. Therefore, additional measures should be taken to enforce GHG emission reductions in all resource consuming sectors. The preliminary assessment of the NECP targets suggests that most countries have reported low ambition and contribution, considering that more integrated efforts are needed to collectively achieve the EU energy efficiency targets. The lack of sector-specific targets in existing national climate policies and goals could be one of

Table 6
Historical indicator changes and national targets projected in the NECPs (European Commission, n.d.-b, n.d.-c, n.d.-a).

	2010	2019	Target 2020	Target 2030
Primary energy consumption, Mtoe				
Latvia	4.6	4.6	5.4	4.3
Lithuania	6.5	6.2	6.5	10.2
Estonia	5.6	4.7	6.5	5.5
Share of renewable energy sources, %				
Latvia	30%	41%	40%	50%
Lithuania	20%	26%	23%	45%
Estonia	25%	32%	25%	42%

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. The results show that the Kaya identity decomposition method can be applied by national authorities to measure the effectiveness of existing climate change policies and to preliminarily assess progress towards the achievement of the climate change mitigation targets.

CRediT authorship contribution statement

Kristiāna Dolge: Formal analysis, Conceptualization, Methodology, Writing - original draft, Investigation, Data curation, Visualization. **Dagnija Blumberga:** Formal analysis, Methodology, Conceptualization, Validation, Supervision.

Declaration of Competing Interest

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

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PAPER 11: COMPOSITE RISK INDEX FOR DESIGNING SMART CLIMATE AND ENERGY POLICIES

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Composite risk index for designing smart climate and energy policies

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ABSTRACT

This study presents an innovative model for a comprehensive, in-depth risk assessment of climate and energy policies. A risk matrix framework combined with a composite index methodology is 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 model was applied to assess five different climate policy instruments, using both an ex-post and ex-ante assessment. The results highlight the critical risk factors for each policy instrument and identify existing policy vulnerabilities that require immediate mitigation action. The model could be used for decision-making at all levels of government and serve as a valuable tool for designing sustainable and successful environmental policies.

1. Introduction

1.1. Background

Climate change, increasing global energy demand and environmental degradation are considered to be among one of the main challenges of modern economy (European Commission, 2019). To combat these issues urgent and decisive climate action is required (European Commission, 2018). The Paris Agreement is the first multilateral agreement on global action towards achieving a reduction of world's greenhouse gas emissions (European Commission, 2016). In the context of the targets set under the Paris Agreement the recently introduced European Green Deal sets an ambitious goal for Europe to become the first climate-neutral continent by 2050 (European Commission, 2020). The strategic goals of the Paris Agreement and European Green Deal will steer all countries towards transition of clean energy. However, to ensure that this transition is successful significant changes and adaptations in the entire policy spectrum at both international and national levels are required which includes the implementation of various interacting policy instruments, concrete government action plans, and strategic policy frameworks (European Commission, 2016).

Carefully designed climate policy is the main cornerstone in order to turn the ambitious commitments into determined actions (Gkonis et al., 2020). While the United Nations and European Commission might impose country specific mandatory obligations and environmental targets, each Member State has its own responsibility to establish necessary regulatory frameworks and policies in order to stimulate the achievement of these targets (Noothout et al., 2016). Although there is a great diversity of policy instruments in the Member States, there is a common problem faced by all countries: How to ensure that the policies implemented do not fail to achieve their original objectives, and how to eliminate the risks that the expected results will not be achieved?

Performing a due diligence which includes a detailed risk assessment is one of the approaches that could be utilized in order to anticipate risks and factors that influence the potential success or failure of designed policies. Therefore, the aim of the research is to develop a tool for an in-depth climate policy risk evaluation that could potentially be used by the governments during the decision-making and policy implementation process. A novel methodology which combines risk matrix framework and composite index methodology is presented and applied for a case study of Latvia to evaluate five different climate policy instruments or projects such as (1) the construction of wind energy park, (2) energy efficiency monitoring system program, (3) the climate financial instrument (CCFI), (4) development of distributed energy generation, and (5) development of centralized energy generation.

1.2. Research on energy and climate policy risk assessment

Risk assessment in energy policy has gained importance in recent years, and the academic literature offers a wide range of methods for measuring risk. However, there is no consensus among scientists on a universal model that could be applied to obtain full-fledged assessment of the uncertainties and ambiguities in development pathways towards low-carbon energy systems.

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A study by (Ortiz and Leal, 2020) examines the practices for evaluating the sustainability and effectiveness of energy policies found in academic papers from around the world. The results show that the majority (52%) of policy evaluation studies use an ex-post evaluation, a much smaller number (15%) apply an ex-ante approach to energy policy evaluation, and only 2 out of 66 papers use a combined ex-post and ex-ante evaluation approach. The majority (29%) of studies use a qualitative approach to evaluation, followed by statistical (26%) and scenario analyses (18%). The authors create a list of 60 energy policy concerns found in academic research. These were grouped into 4 main categories - environmental, economic, social and institutional - which were used by the researchers to evaluate the effectiveness of the policy. Economic factors have been studied most often and have been included in almost all studies. Based on the findings of the review, the authors highlight the key indicators identified by the researchers - affordability, accessibility, competitiveness level, environmental impact, equity, health and efficiency of the governance. The study advocates the use of an ex-ante approach to avoid pitfalls in achieving energy policy goals (Ortiz and Leal, 2020).

In another study (Ioannou et al., 2017) the risk assessment methods used in the development of sustainable energy systems and infrastructures are examined in detail. The authors argue that with the rapid increase in renewable energy and energy efficiency investment projects, the risks associated with the implementation and integration of these technologies are also increasing, making it increasingly urgent to develop an integrated risk assessment framework. The study categorizes risks into 6 main categories (political, economic, social, technological, legal, environmental) each divided in representative sub-categories. The authors summarise the most common risk assessment methods and divide them into quantitative and semi-quantitative approaches. Quantitative methods assess risks using probability distributions or variance means such as mean variance portfolio, real options analysis, Monte Carlo Simulation, optimization methods, to analyse parameters that are statistical, such as economic and technical chremistica. In contrast, socio-economic factors such as regional development and public acceptance, which are not statistical and are referred to as semi-quantitative, are assessed using multi-criteria decision analysis or scenario analysis. The report concludes that there is no universal method that can be applied to capture all the nooks and crannies of the phenomena, as each method is unique in terms of the assumptions made and the techniques used to obtain the results [2.

Felder and Kumar (2021) provide an overview of different types of models for deep decarbonization Different types of deep decarbonization models are reviewed by Felder and Kumar (2021). The authors argue that by identifying risks, concerns, and complexities of sustainable energy systems, the value of energy policy modelling can be greatly enhanced. By integrating risk factors into modelling, future pathways can be more realistically modelled and predicted. Furthermore, the identification of potential uncertainties enables the creation of socially and politically acceptable long-term decisions (Felder and Kumar, 2021).

A three-stage model for risk assessment of renewable energy investments was developed by (Kul et al., 2020). The model integrates Delphi, AHP and fuzzy WASPAS methods used to assess 6 risk factors (economic & business, technical, political & policy, market, environmental, social), each explained by three to five sub-risk factors in each dimension. Risk analysis integrated the opinions from ten experts from different economic sectors of Turkey. The results from the questionnaires, interviews and group discussions served as input parameters for Delphi and AHP method. The study concludes that economic and business risks have the greatest impact on the success of renewable energy investment projects, followed by market risks, political and policy risks, and technical risks. Environmental and social risks were rated as least impactful compared to the other risk categories. The authors recommend that governments and policymakers use risk assessment models to identify, avoid, and mitigate the risk factors of low-carbon energy transition policies and strategies (Kul et al., 2020).

Another model was developed by (Gaudard and Romerio, 2020) which provides a framework for assessing risk uncertainty and ambiguity in sustainable energy transition policies. A two-stage procedure for measuring risk and uncertainty is developed. First, the “acuity scale” is used to combine the probability and impact levels of risks to categorize their degree of importance. Then, a taxonomy is applied to categorize risk into gamble and butterfly uncertainties according to risk impact and probability of occurrence. Using the case study of the Swiss energy sector, it is found that the degree of doubt is the most important determinant when considering effective approaches to risk optimization. Sufficient risk assessment enables the identification of factors that may have been over- or underestimated in the implementation of energy sustainability strategies (Gaudard and Romerio, 2020).

The importance of risk assessment in energy systems planning is also highlighted in a study by (Koltsaklis and Dagoumas, 2018) that reviews the latest General Expansion Planning (GEP) methods. The authors argue that awareness of risks helps identify and circumvent critical challenges in low-carbon investments. Moreover, careful strategies could be applied to directly hedge the identified risks and facilitate investors’ decision-making. Similar to other research, this study classifies risks and uncertainties into different categories, such as political, regulatory, economic, technical, social, environmental, and climate (Koltsaklis and Dagoumas, 2018).

A study by (Siksnelyte et al., 2018)examines different methods of decision making in energy policy research. The authors argue that the use of sustainability assessment has grown rapidly in recent decades due to the increasing complexity of decision making associated with the transition to low-carbon energy systems. Based on the review of 105 academic papers on energy sustainability and the application of multi-criteria decision making methods (MCDA), the study provides SWOT analysis for each method used. The results show that AHP, TOPSIS, PROMETRE and fuzzy set methods are most commonly used by researchers due to their advantageous features such as ease of application, comprehensive interpretation of results and rational assumptions. Other methods such as WASPAS, PROMETHEE, VIKOR, ELECTRE, ASPID and MULTIMOORA are less commonly used (Siksnelyte et al., 2018).

2. Methodology

The methodology of this study is constructed based on previous research describing a range of risk factors affecting the success or failure of energy policy and techniques for measuring them. Integrated evaluation of risks is extremely essential for decision-making since it might be complicated to estimate the riskiness and inconsistency of a project or policy based on too many factors and indicators (Felder and Kumar, 2021). To address this challenge, most studies use the multicriteria decision making analysis (MCDA) method because it has the advantage of allowing the integration of factors that are not statistical and are based on a qualitative assessment (Siksnelyte et al., 2018). However, the disadvantage of MCDA lies in the presentation of the results, which does not show the influence of the individual factors on the overall result (Balode et al., 2021). Therefore, this study uses composite index methodology that allows to incorporate various risk factors into a composite risk index (RI), assign a risk class for all the evaluated policies and identify risk indicators that have the greatest impact on the success or failure of the policy. The composite index methodology is widely used in sustainability assessment studies and has gained increasing recognition among academics and international organizations in recent years, as it allows the comparison of alternative policies and the identification of critical aspects in each policy instrument (Balode et al., 2021).

Risk index in this study is defined as a composite measure of various risk indicators that impact the success and sustainability of the implemented policy, project or program in the energy sector. The procedure of risk evaluation and risk index (*RI*) calculation consists of several interconnected parts that are illustrated in Fig. 1 and described in detail hereinafter.

2.1. Identifying and defining risk categories

An extensive literature review was conducted on risks and barriers in energy, bioeconomy and climate projects, programs and policies. Based on the findings from the previous studies, six main risk categories, each with four risk indicators, were identified and summarized in Table 1.

Political risk category reflects the dysfunctionality of the existing legal system and regulatory risks that hinder the development of renewable energy and climate change mitigation programs. Political risk indicators measure the lack of certainty created by sudden changes in policy and support schemes; the risk of poorly designed policy instruments that lack clear guidelines, vision, conditions and requirements; the lack of government incentives and political will to promote policy; and the limited long-term planning and durability of legislation.

Technical risk category incorporates risks related to the availability of technical and human capital and productivity. Technical risks are related to various technical challenges encountered in the implementation of a particular project, such as limited access to required technologies and infrastructure, limited technical capacity, unreliability of existing technologies by stakeholders, lack of knowledge, experience and training of staff. Technical pitfalls make it difficult to implement climate projects and thus represent a significant barrier to the long-term development of renewable energy.

Economic risk category includes financial and market risks that affect the economic stability and profitability of the operations or investment projects carried out. The risk indicators in the economic risk category reflect the absence of subsidies and government support mechanisms needed to promote policy implementation. In addition, this category includes risk indicators that measure the inefficiency of fiscal and other policy instruments, such as taxation regime for setting tariffs, feed-in tariffs, quota obligation systems, and others. Financial risk is related to limited financing options due to insufficient access to investment and working capital and inefficient operating (OPEX) and capital (CAPEX) expenditures, as well as small market size that limits the ability to take advantage of economies of scale, which is critical for large utility infrastructure projects.

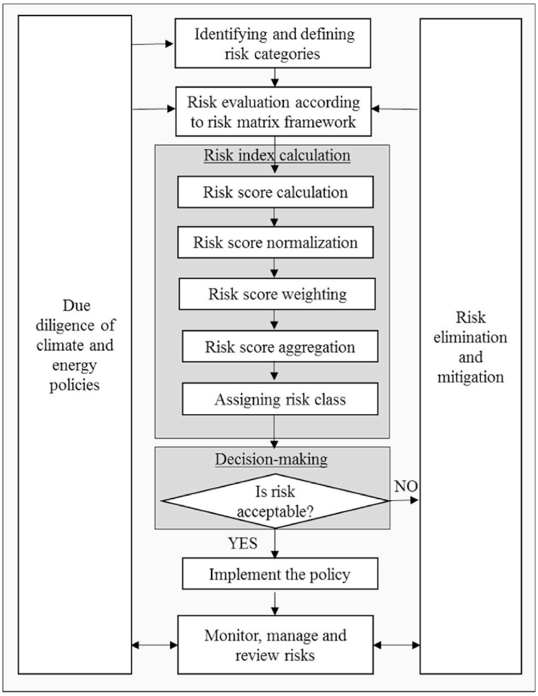


Fig. 1. Developed model for risk evaluation and risk index calculation. Developed by the authors inspired by (Dudek, 2020).

Environmental risk category consists of risk indicators that measure the impact on the environment that results from the implementation of policies or projects. Environmental risks include the risk of environmental damage and the creation of direct negative impacts on the environment, the risk of not achieving the reduction of the carbon footprint, insufficient consideration of the life cycle of a project or program (centralized vs. decentralized, regional vs. global, urban vs. rural), the risk of creating indirect environmental damage (e.g. if the project promotes the consumption of additional resources such as energy, materials, labor, etc.) or the environmental risks of a project are unknown.

Social risk category refers to social issues that have a significant impact on the implementation of the project or policy. The risk indicators in the social risk category reflect limited public acceptance, public comfort with the existing situation, unwillingness to change, and lack of public knowledge that create local challenges and barriers to achieving the project or program's climate objectives. In addition, the lack of available labor, which limits the capacity for adequate project implementation, is also considered a significant social problem and is therefore included in the category of social risks.

Administrative risk category includes risks related to the sufficient provision of support services and information. Administrative risks are measured against a list of risk indicators, such as inadequate and insufficient information dissemination, dysfunctional project administration, management and programme/project monitoring, high bureaucratic burden, complex approval and administrative procedures, lack of administrative institutions, support services, professional research institutions, and others.

2.2. Risk evaluation according to risk matrix framework

Risk matrix framework is applied for the evaluation of identified risk indicators. Risk matrix is a comprehensive and simple risk evaluation technique that is commonly used to assess the level of risk based on which reasonable and justified decisions on the most important priorities for action could be determined (Peace, 2017).

In practice risk matrix is frequently used as the main risk prioritization technique in risk management frameworks and software packages. For instance, risk matrix is embedded in ISO3100 standard (Peace, 2017) 2017) which is directly focused on providing an effective set of risk management practices and guidelines for the activities and processes of organizations at all levels of governance (ISO, 1000).

In this research risk matrix framework is chosen as the most appropriate technique for the allocation of risk grades to obtain quantitative measurement since it will allow to rank and compare the risk categories and highlight the most critical risks that require immediate stakeholder attention (Peace, 2017).

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 (Mcmahan and Gerlak, 2020). The level of each component is assessed according to a five-point scale as outlined in Table 2. Therefore, two grades are assigned for each risk indicator – one for the risk likelihood and another for the risk consequence.

Scores from 1 to 5 of risk assessment scale reveal that the higher grade represents the higher risk impact. It applies for both criteria – likelihood and consequence (Xu et al., 2018). Risk score for the

Table 1
Selected risk indicators and risk classification.

Risk category	Risk indicator	Risk description	Reference
Political	Legal	Sudden changes in the policy and support schemes	(Noothout et al., 2016), (Ioannou et al., 2017), (Gatzert and Kosub, 2016)– (Watts, 2011)
	Regulatory	No clear guidelines, vision, conditions and requirements of the implemented legislation and regulatory	(Noothout et al., 2016), (Kolios et al., 2016), (Wu and Zhou, 2019)–(Mirza et al., 2009)
	Incentives	Lack of government incentives and limited promotion of the policy	(Kolios et al., 2016), (Painuly, 2001), (Mirza et al., 2009)
	Long-term	Limited long-term planning and objectives of the policy (overlooking important details for legislation)	(Kolios et al., 2016), (Laumanns et al., 2004), (Lawrence et al., 2020)
Technical	Infrastructure	Limited access to technology and infrastructure	(Noothout et al., 2016), (Ioannou et al., 2017), (Gatzert and Kosub, 2016), (Kolios et al., 2016), (Wu and Zhou, 2019)– (Mirza et al., 2009)
	Operation	Limited technical capacity	(Noothout et al., 2016), (Wu and Zhou, 2019)– (Mirza et al., 2009), (UNEP , 2008)
	Maintenance	Unreliability of technologies	(Ioannou et al., 2017), (Kolios et al., 2016), (Watts, 2011), (Painuly, 2001), (Mirza et al., 2009), (UNEP, 2008), (Rolik, 2017)
	Productivity	Lack of employee knowledge, experience and training	(Noothout et al., 2016), (Ioannou et al., 2017), (Kolios et al., 2016), (Painuly, 2001), (Mirza et al., 2009), (Rolik, 2017), (Huenteler et al., 2016)
Economic	Aid	Lack of subsidies and support mechanisms to stimulate the implementation of the policy	(Noothout et al., 2016), (Kolios et al., 2016), (Wu and Zhou, 2019)–(Mirza et al., 2009), (Lawrence et al., 2020), (IRENA, 2016), (Warren, 2020)
	Policy	Inefficient fiscal and other policy instruments (taxation regime for the tariff determination, feed-in tariffs, quota obligation scheme, etc.)	(Noothout et al., 2016), (Ioannou et al., 2017), (Painuly, 2001), (Rolik, 2017), (Unlocking Renewable Energy Investment: the Role of Risk Mitigation, 2016)
	Financial	Limited financing opportunities (insufficient access to investment and operating capital)	(Noothout et al., 2016), (Ioannou et al., 2017), (Kolios et al., 2016), (Watts, 2011), (Painuly, 2001), (Mirza et al., 2009), (Rolik, 2017), (Unlocking Renewable Energy Investment: the Role of Risk Mitigation, 2016)
	Market	Inefficient production and operation costs (OPEX), high capital and investment costs (CAPEX), small market size, limited opportunities for economies of scale	(Noothout et al., 2016), (Ioannou et al., 2017), (Kolios et al., 2016)–(Mirza et al., 2009), (Unlocking Renewable Energy Investment: the Role of Risk Mitigation, 2016)
Environmental	Environment	Risk of environmental damage and creation of direct negative effect on the environment	(Ioannou et al., 2017), (Gatzert and Kosub, 2016), (Kolios et al., 2016), (Painuly, 2001), (UNEP, 2008), (Linkov et al., 2006)
	Emissions	Risk of not achieving the reduction of carbon footprint	(Ioannou et al., 2017), (Kolios et al., 2016)
	Life cycle	Insufficient provision and assessment project/program life cycle (centralized vs decentralized, regional vs global, urban vs rural)	(Ioannou et al., 2017), (Kolios et al., 2016)
	Resources	Risk of creating indirect environmental damage (e.g. stimulates the consumption of additional resources such as energy, materials, labor, and others) or unknown environment risks	(Kolios et al., 2016), (Painuly, 2001)
Social	Acceptance	Limited public acceptance	(Noothout et al., 2016), (Ioannou et al., 2017), (Gatzert and Kosub, 2016), (Kolios et al., 2016), (Painuly, 2001), (Linkov et al., 2006)
	Adaptability	Public comfort with the existing situation and unwillingness to change	(Noothout et al., 2016), (Painuly, 2001), (Warren, 2020)
	Knowledge	Lack of public knowledge	(Noothout et al., 2016), (Kolios et al., 2016), (Mirza et al., 2009)
	Labor	Lack of available labor force that limits the capacity for adequate implementation of the project	(Ioannou et al., 2017), (Painuly, 2001)
Administrative	Communication	Inadequate and insufficient information dissemination	(Ioannou et al., 2017), (Painuly, 2001)
	Project management	Dysfunctional project administration, management and program/project monitoring	(Rolik, 2017), (Thollander et al., 2020)
	Bureaucracy	High bureaucracy and complex approval/administration process	(Noothout et al., 2016), (Ioannou et al., 2017), (Gatzert and Kosub, 2016), (Kolios et al., 2016)
	Institutions	Lack of administrative institutions, support service, professional research institutions	(Noothout et al., 2016), (Painuly, 2001), (Mirza et al., 2009), (Lawrence et al., 2020)

likelihood criteria is determined based on the probability of risk occurrence. The higher the probability, the higher risk likelihood grade. The same is true for the risk consequence grade, where the higher grade represents the more serious consequence of risk.

2.3. Risk score calculation

When the grades for both criteria are assigned, the risk scores for all risk indicators are calculated. Risk score is calculated as the multiplication between the grades of risk likelihood and risk consequence as demonstrated in Eq. (1).

$$R_i = R_{likelihood} \times R_{consequence}, \tag{1}$$

where R_i is a risk score, $R_{likelihood}$ is the obtained score of a risk likelihood, $R_{consequence}$ is the obtained score of a risk consequence.

2.4. Risk score normalization

Obtained risk scores are normalized using min-max normalization technique. Normalized risk scores are calculated according to formula demonstrated in Eq. (2).

$$R_{Ni} = \frac{R_i - R_{min}}{R_{max} - R_{min}}, \tag{2}$$

where R_{Ni} is the normalized risk indicator score, R_i is the calculated actual risk score, R_{min} is the minimum score of the risk matrix, R_{max} is the maximum score of the risk matrix.

Since a five-point risk matrix scale is used in this study, then the minimum score of risk matrix is equal to 1 (1 × 1), and maximum score is equal to 25 (5× 5). Therefore, both of these values are used in the normalization formula. Normalized risk matrix values are outlined in Table 3.

The advantage of the min-max normalization is that it normalizes risk scores in a scale from 0 to 1, where 0 represents the lowest risk score, and value of 1 represents the highest risk grade. Normalizing values to a particular scale is necessary for risk index calculation since it would allow to easily interpret, and rank risks based on their level of impact (Dolge et al., 2020). To the authors' knowledge min-max normalization is not used in other risk matrix application studies, therefore the proposed normalized risk matrix in this study is a novelty since innovative approach of combining risk matrix framework with composite index calculation techniques is applied. Other normalization techniques used in the construction of composite indices, such as z-score normalization, distance-based normalization, and ranking (Mazziotta and Pareto, 2013), result in more scatter in the scales of the results, making them difficult to interpret and apply immediately. However, min-max normalization, which is used in many composite sustainability indices (Dolge et al., 2020), (Mazziotta and Pareto, 2013), is more suitable for relative comparisons, e.g. between different risk categories and policies.

2.5. Risk score weighting

After risk score normalization weights are assigned for each risk indicator. In this study equal weighting technique is used which means that weights for each risk indicator depend on the total number of indicators in the particular risk category.

In the existing literature and composite index application studies there is no consensus reached by the scientists about the choice of the most appropriate and objective weighting technique (Mazziotta and Pareto, 2013). The authors of this study believe that equal weighting provide more freedom of result interpretation since each person can make a judgement of indicator impact levels on its own. While other widely used weighting methods such as analytic hierarchy process (AHP) method is highly reliable on subjective judgement that might produce misleading results (Zhou and Yang, 2020). Moreover, from the performed literature review from which risk indicators were identified, it was concluded that all risks are interconnected and their impact levels on the implementation of the particular policy or project for each country are different. In this study AHP weighting method was also tested and the obtained results did not substantially differ from the equally weighted values.

Equal weights are assigned for both – risk sub-index values for each risk category and for the final risk index value. Since there are 4 risk indicators in each risk category then a weight of 0.25 (1/4) is applied for the calculation of risk sub-indices. However, since there are six main risk categories, then a weight of 0.17 (1/6) is used for the calculation of risk index.

Risk category sub-index is obtained by multiplying the normalized risk indicator values (R_{Ni}) with their corresponding weight in the particular risk category (w_i). Afterwards the values are aggregated into a final sub-index value as demonstrated in Eq. (3).

$$R_{Ci} = \sum w_i \times R_{Ni}, w_i = \frac{1}{n_i}, \tag{3}$$

where R_{Ci} is the risk sub-index for a group of risk categories i (political, $i = 1$, technical, $i = 2$, economic, $i = 3$, environmental, $i = 4$, social, $i = 5$, administrative, $i = 6$), w_i is the determined weight of the risk indicator in the representative risk category, R_{Ni} is the normalized risk indicator value, n_i is the number of risk indicators in a particular risk category.

Table 2
Evaluation scales for the risk indicator assessment.

Score	Likelihood (p - probability)	Consequence
5	Almost certain (95%–100%)	Catastrophic
4	Likely (70% - <95%)	Major
3	Possible (30% - <70%)	Moderate
2	Unlikely (5% - <30%)	Minor
1	Rare (0% - <5%)	Negligible

2.6. Risk score aggregation

Final step for risk index construction involves the aggregation of the calculated risk sub-indices according to Eq. (4). The basic risk index (RI) hierarchy is illustrated in Fig. 2.

$$RI = \sum w_C \times R_{Ci}, w_C = \frac{1}{n_C}, \tag{4}$$

where RI is the final risk index, w_C is the determined weight of the risk category, R_{Ci} is the risk category sub-index value, n_C is the number of risk categories in the risk evaluation model.

2.7. Assigning risk class

When the risk index scores are obtained and summarized, it is possible to assign risk classes for the evaluated projects or policy instruments. Risk class is defined according to the values of the normalized risk matrix that is outlined in Table 3. Risk class of a policy is determined based on its final risk index score. Overall, there are four main risk classes – low risk (0.00–0.10), moderate risk (0.11–0.25), high risk (0.26–0.50), and extreme risk (0.51–1.00).

3. Results and discussion

3.1. Case studies

The consistency and effectiveness of the model was validated in the case study of Latvian climate and energy policy. In total, five policy instruments were evaluated. The selected policy instruments for the case study evaluation are summarized in Table 4. The diversity of the selected case studies is intended to demonstrate that the proposed model is suitable for different types of policy evaluations and is not limited to a single specific project, policy or program evaluation. In addition, the model aims to prove that it is possible to conduct evaluations for historical and future policies. The model allows for both (1) a comprehensive ex-post evaluation to draw valuable conclusions based on historical experience and (2) an ex-ante evaluation for future policies currently under discussion in the public and at the government level to identify the best alternatives for the long-term sustainable development of the energy sector.

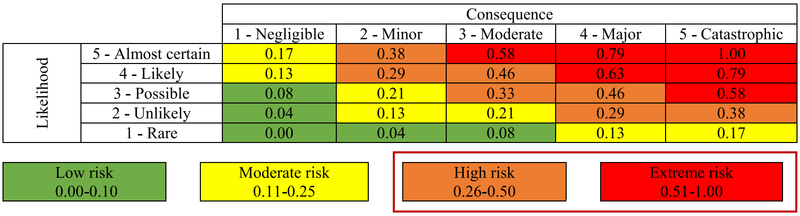
Construction of wind energy park is a private renewable energy investment project in Latvia that projects to construct up to 35 wind turbines with a capacity of more than 100 MW by the year of 2022 and therefore, significantly increasing the overall wind energy share in the total electricity demand in Latvia (Network, 2019).

Energy efficiency monitoring system program is a policy instrument that was established in Latvia in 2017 by the Ministry of Economics of the Republic of Latvia. The program is a part of Energy Efficiency Law which sets specific requirements for large companies and large energy consumers in order to stimulate enterprises to implement energy efficiency activities and reduce their overall energy consumption (Kubule et al., 2020).

The climate financial instrument (CCFI) is 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. The program was introduced in order to meet the national greenhouse gas reduction targets set by the United Nations under in the Kyoto Protocol (Asere and Blumberga, 2015).

The question about what the most sustainable energy generation method in Latvia is and whether more emphasis should be made on promoting and supporting the distributed energy generation instead of the centralized energy systems remain unsolved. Both strategies involve issues and challenges that should be investigated in more detail to examine the risk level of each alternative. Therefore, both of the case

Table 3
Normalized risk matrix.



		Consequence				
		1 - Negligible	2 - Minor	3 - Moderate	4 - Major	5 - Catastrophic
Likelihood	5 - Almost certain	0.17	0.38	0.58	0.79	1.00
	4 - Likely	0.13	0.29	0.46	0.63	0.79
	3 - Possible	0.08	0.21	0.33	0.46	0.58
	2 - Unlikely	0.04	0.13	0.21	0.29	0.38
	1 - Rare	0.00	0.04	0.08	0.13	0.17

Low risk 0.00-0.10
Moderate risk 0.11-0.25
High risk 0.26-0.50
Extreme risk 0.51-1.00

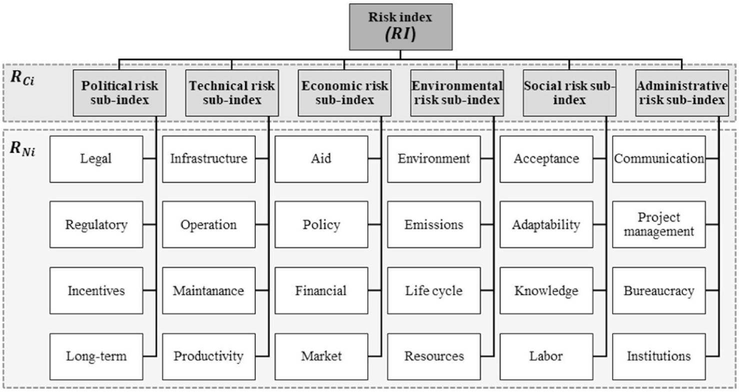


Fig. 2. Basic risk index hierarchy. Developed by the authors inspired by (Krajnc and Glavič, 2005).

Table 4
Selected policy instruments for case study evaluation.

	Name of the instrument	Type of instrument	Type of evaluation
Case 1	Construction of wind energy park	Project	Ex-ante
Case 2	Energy efficiency monitoring system program	Program	Ex-post
Case 3	The climate financial instrument (CCFI)	Program	Ex-post
Case 4	Development of distributed energy generation	Policy	Ex-ante
Case 5	Development of centralized energy generation	Policy	Ex-ante

studies are evaluated in the developed risk assessment model and risk index is calculated for both scenarios.

3.2. Experts

Each case study was evaluated by a group of experts who have extensive professional experience in the energy sector and a broad knowledge of energy policy and related challenges. The description of the selected experts is summarized in Table 5.

Each expert received a comprehensive description of the selected case studies and was asked to complete a risk assessment form. The risk assessment form included a detailed description of the identified policy risk indicators and their representative risk categories, as well as the necessary information on the five-point scale for the assessment of the risk probability and risk consequence criteria.

For all selected case studies in this research, the industry experts assigned two scores for each risk indicator. The results of the risk evaluation forms were summarized in a mathematical model developed by the authors of this study. The results of the risk sub-indices and the overall index represent the mean of the experts' scores.

3.3. Results from the case study evaluation

Table 6 summarizes the average total risk scores for each risk indicator from the expert evaluation These results show which risk indicator contributed the most in each risk category for each case study. Limited long-term planning and objectives of the policy (overlooking important details for legislation) is rated on average as the highest risk factor in the political risk category. Lack of employee knowledge, experience and training is evaluated on average as the highest risk indicator in technical risk category. Inefficient fiscal and other policy instruments (taxation regime for the tariff determination, feed-in tariffs, quota obligation scheme, etc.) is rated as highest risk in economic risk category, risk of not achieving the reduction of carbon footprint in environmental risk category, limited public acceptance in social risk category and high bureaucracy and complex approval/administration process in administrative risk category.

The risk index results of the case study evaluation are summarized in Table 7. The values of the risk indices show that all the case studies assessed are in a high-risk category according to the risk classes defined in Table 3. In general, no wide distribution of results is observed among the analyzed case studies and the values of the overall risk index range from 0.36 to 0.43. The risk index takes values in a scale from 0 to 1, therefore the obtained results allow a simple interpretation that the higher the risk index value, the higher the risk of the analyzed case study.

The results show that there are significant differences in the overall risk levels between the different energy policy instruments. The differences occur in all six categories of the risk index - political, technical, economic, environmental, social and administrative. Fig. 3 illustrates the comparison of the sub-index values determined for the different policy instruments examined.

The highest overall risk index value of 0.43 was achieved by the energy efficiency system monitoring program (Case 2). The program showed particularly high risk scores for the policy (0.55), administrative (0.49), and social (0.48) sub-indices. The high scores obtained in these categories are consistent with the findings of the studies by Kubule et al. (2020) and Ločmelis et al. (2020), which assess the initial results of the program and identify several weaknesses related to the design of the policy instrument and program administration (Kubule et al., 2020), (Ločmelis, 2020). First, the program was launched by the Ministry of Economy with considerable delay in order to meet the requirements of the EU Energy Efficiency Directive, suggesting that the government lacked the incentive and political will to promote the policy. As a result, the policy was poorly designed and lacked clear guidelines, a long-term vision, and a detailed and comprehensive description of the conditions and requirements for the program's target groups. In addition, sudden changes and additions were made to the Energy Efficiency Law website, which affected the reliability of the program and created distrust. Secondly, information about the program was poorly communicated to the main target groups, which led to confusion and limited public acceptance of the program, so that the intended objectives were not achieved. Thirdly, the overall management of the program was inadequately carried out and the monitoring system developed did not collect all the necessary data crucial for a sufficient assessment of the program objectives achieved. It can be concluded that the above factors are also reflected in the representative risk sub-indices, as the Energy Efficiency Monitoring System Program (Case 2) received the highest score in the administrative risk sub-index category and the second highest score in the social risk sub-index category compared to the other policy instruments evaluated in this study. The breakdown of the results by risk sub-categories shows that the critical aspects of the program are related to inadequate regulatory design, administrative and social aspects. Therefore, the overall risk level of the program can be reduced by addressing the weaknesses, especially in these areas.

The lowest total risk index was found for the development of centralized energy generation (case 5) with a risk index value of 0.36. Despite the lowest overall risk index score, this case study achieved the highest score in the political risk sub-index category with a score of 0.58. When analyzing the indicators that most influenced a high political sub-index score, it was found that almost all experts gave the highest scores to the Legal and Long-term Risk indicators. It can be concluded that the highest risk to the development of centralized energy generation is associated with the sudden changes in policies and support mechanisms by the government, as well as limited long-term planning and objectives of the centralized energy generation policies, including overlooking important details for legislation. Comparing the results with an alternative policy scenario, i.e., the development of distributed energy generation (Case 4), we can see that although the policy risk for distributed energy generation is rated significantly lower, the overall risk index reaches a value of 0.41, which is 0.05 higher than that for the development of centralized energy generation. The development of distributed energy generation (case 4) reaches the highest economic risk sub-index. This is due to market risk, which leads to limited opportunities for economies of scale, resulting in inefficient production and operating costs (OPEX) and high capital and investment costs (CAPEX). In addition, there are currently no efficient fiscal and other policy instruments, such as an efficient tax regime for setting tariffs for distributed energy or other instruments that would promote the long-term development and profitability of distributed generation. These two factors were highlighted by the experts as the positions of particularly high risk.

Table 6
Average total risk scores from the expert evaluation.

		Case 1	Case 2	Case 3	Case 4	Case 5
Political	Legal	14.00	12.75	9.00	11.20	16.40
	Regulatory	14.60	13.50	7.75	12.80	14.60
	Incentives	14.60	14.00	8.00	12.00	11.40
	Long-term	14.40	16.25	13.75	13.60	16.20
Technical	Infrastructure	7.00	7.25	8.00	10.80	5.40
	Operation	7.20	7.75	9.00	10.00	5.00
	Maintenance	9.60	7.00	9.25	11.80	8.20
	Productivity	10.60	12.25	15.00	9.00	8.00
Economic	Aid	9.00	12.00	8.25	13.00	8.20
	Policy	12.60	13.00	9.25	13.20	10.00
	Financial	8.80	11.00	10.00	10.20	9.20
	Market	9.40	10.25	12.25	13.60	10.60
Environmental	Environment	9.00	4.25	6.25	10.80	10.80
	Emissions	7.40	12.00	17.25	12.80	12.40
	Life cycle	7.40	13.25	9.50	10.00	10.00
	Resources	9.60	9.75	7.75	9.00	8.00
Social	Acceptance	17.60	11.00	8.00	10.00	7.40
	Adaptability	13.20	12.75	7.50	10.60	6.20
	Knowledge	13.00	12.25	10.50	11.00	6.20
	Labor	7.40	14.00	8.50	7.40	8.60
Administrative	Communication	13.20	10.25	7.00	9.60	9.80
	Project management	9.20	17.00	10.00	8.00	6.80
	Bureaucracy	15.40	12.25	9.75	11.80	10.00
	Institutions	10.00	17.00	7.00	8.00	10.80

Table 7
Summary of the risk index results from the case study evaluation.

	Case 1	Case 2	Case 3	Case 4	Case 5
Political risk sub-index	0.56	0.55	0.34	0.46	0.58
Technical risk sub-index	0.32	0.34	0.41	0.38	0.22
Economic risk sub-index	0.37	0.39	0.37	0.47	0.33
Environmental risk sub-index	0.31	0.33	0.43	0.44	0.38
Social risk sub-index	0.49	0.48	0.36	0.38	0.27
Administrative risk sub-index	0.46	0.49	0.29	0.36	0.36
Total risk index	0.42	0.43	0.37	0.41	0.36

The second highest risk index value of 0.42 was reported for the construction of a wind energy park (case 1). In general, a similar

Table 5
Selected group of experts for case study evaluation.

	Description about the expert's role in the industry
Expert 1	More than 40 years of professional, academic and scientific experience in energy sector and environmental engineering science
Expert 2	More than 25 years of professional and scientific experience in energy and utilities sector, and environmental science
Expert 3	More than 20 years of professional and scientific experience in energy sector, electrical engineering and environmental science
Expert 4	More than 10 years of professional, academic and scientific experience in energy sector and environmental engineering science
Expert 5	More than 5 years of professional experience in the field of energy policy and program implementation and monitoring

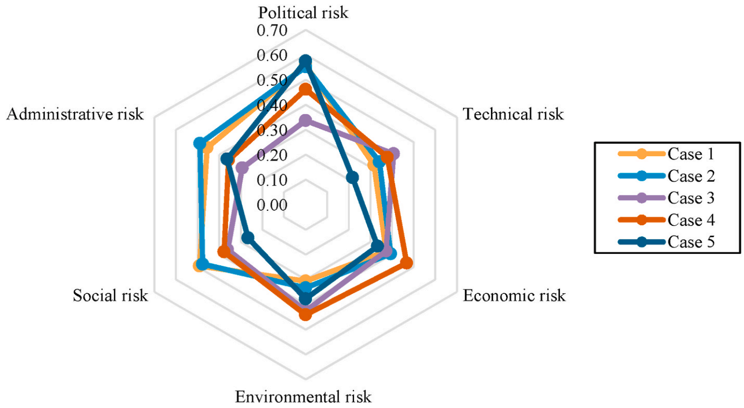


Fig. 3. The values of risk sub-indices from the case study evaluations. Developed by the authors inspired by (Wu and Zhou, 2019).

distribution of scores was found as for the energy efficiency monitoring system program (case 2). However, the construction of a wind energy park achieved the highest score compared to the other policy instruments, namely the score of 0.49 in the social sub-index category. The high score in this category is justified as the project has generated strong public debate and agitation over the last two years and has faced several local challenges (Network, 2019). The inadequate, insufficient and misleading dissemination of information, combined with a populist approach to communication, has led to a biased public perception and strong antipathy towards the project (Petersone, 2019). Limited public acceptance, unwillingness to change and lack of public knowledge are therefore one of the main risk factors hindering the development and implementation of the project. Apart from this, the project also faces high political risk, especially in terms of lack of clarity in the long-term vision of the regulators and lack of incentives and political will from the government to promote project implementation. In addition, the project faces a high level of bureaucracy related to existing land use regulations and permits that limit the availability of land needed to increase the capacity of installed wind turbines. (Petersone, 2019).

The second lowest risk index value of 0.37 was found for the climate finance instrument (case 3). However, it should be noted that the environmental risk sub-index score of 0.43 was the highest among all other risk categories for this instrument. Specifically, the climate financial instrument scored the highest for the risk of not achieving emission reductions and carbon footprint reductions. This result highlights a contradiction in policy, as the main purpose of establishing the instrument was directly aimed at reducing GHG emissions in all major sectors of the Latvian economy. This leads to the conclusion that the policy instrument may have been only conceptual and failed in achieving its main objective.

3.4. Discussion

Previous research on risk assessment in energy policy has found that economic factors are most often rated as particularly influential and critical to the development of sustainable energy systems. To evaluate which factor was evaluated as the most impactful in this study, the average sub-index scores of all the case studies were analyzed together. It was found that political risk was the highest compared to the other risk categories. Moreover, political risk was highest for almost all policy instruments assessed, with the exception of the climate finance instrument (see Table 6). These findings are in line with the results of the study by Chebotareva et al. (2020), which concludes that political risk is considered the most dangerous in Latvia and seems to rank first among the other risks observed in renewable energy projects (RES), such as grid access risk, administrative risk, financial risk, technical and administrative risk, and public acceptance risk (Chebotareva et al., 2020). Moreover, the results are consistent with the findings of a study by Noothout et al. (2016), which examines the impact of risk in investments RES and the role of smart policies for all member states of the European Union and concludes that sudden policy changes and risks are of extremely high importance in policy making in Latvia (Noothout et al., 2016). Another study on investment risks in the renewable energy sector states that political risks are among the most important, as they are directly related to foreign direct investment and changes in international policy requirements (Shimbar and Babak, 2020).

Economic, social and administrative risks were among the second highest according to the averages of all case studies. All three categories had the same average scores and are therefore considered equally important. The authors argue that the social and administrative risk categories are as high as the economic risks because without an adequate support system and the involvement of key target groups, it is very difficult or almost impossible to achieve the main objectives of the policy. Technical risk had the lowest average score compared to the other risk categories. The same conclusion was reached in the study by Kul et al. (2020), that assessed renewable energy investment risk factors in Turkey into five main risk categories - economic, market, policy, technical, environmental and social. Technical sub-risk factors such as grid access, operations and maintenance, project development, construction risk and resource risk were ranked significantly lower than sub-risk factors in other categories. The authors of the study argue that for the successful implementation of renewable energy infrastructure projects, technical feasibility and environmental benefits are not sufficient and other factors such as financial risk, politics, R&D capacity, quality of services and lack of required expertise play the most crucial role (Kul et al., 2020).

3.5. Limitations and suggestions for further research

Overall, the results of the case study evaluations show that the proposed model was successfully approbated and was able to provide valuable insights into the risks of the different climate policy instruments. Nevertheless, it is important to bear in mind that the results are only indicative and should not be interpreted hastily.

One of the main limitations of the model is the possible biases in the different expert assessments, which could lead to potential inaccuracies in the results. As experts may have different perceptions of the case studies and the risk indicators identified, it is suggested that a focus group discussion be held with all experts involved before the case studies are assessed to ensure that the experts are on the same page. Group discussions are effective in achieving more accurate assessment. Studies (Woudenberg, 1991) by and (Kul et al., 2020) note that evaluations that come from interacting groups are more accurate than individual evaluations that are aggregated. Therefore, it is proposed to use the interaction potential of the group to reach a common and more accurate judgement.

In addition, further research could experiment with using different extensions of the risk matrix by using different point scales or criteria for risk assessment. Furthermore, the model is easily adaptable and additional risk categories with representative risk indicators could be added or replaced. In addition, different weighting methods such as the Analytic Hierarchy Process (AHP) method could be used to prioritize the importance of the identified risk categories.

4. Conclusions

In this study, an innovative combination of risk matrix and composite index methodology is applied to develop a risk index for assessing the risk level of climate policies. The risk index is composed of 24 different risk factors grouped into 6 main risk categories - political, technical, economic, environmental, social and administrative. Each risk category consists of 4 explanatory risk indicators.

A risk index and six risk sub-indices were calculated for five climate policy instruments: (1) the construction of wind energy park, (2) energy efficiency monitoring system program, (3) climate financial instrument (CCFI), (4) development of distributed energy generation, and (5) development of centralized energy generation. The results of the model application show that different risk categories are more pronounced for each policy instrument, and the differences occur for almost all representative risk indicators. The advantage of the model is that it allows easy identification of the critical aspects in each policy, thus drawing attention to the positions that require immediate strategic action to reduce and eliminate risks. The proposed model could be used as a tool for policy makers, stakeholders and decision makers to make rational and justified decisions regarding the implementation of sustainable and successful climate policies.

Declaration of competing interest

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

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PAPER 12: WHAT ARE THE LINKAGES BETWEEN CLIMATE AND ECONOMY? BIBLIOMETRIC ANALYSIS

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What are the Linkages between Climate and Economy? Bibliometric Analysis

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Abstract **– Climate change poses a major challenge to capitalist-oriented societies to restructure their economies and adapt to low-carbon measures that, at first glance, may not be the most economically viable option. Therefore, climate-economy models have become increasingly important in environmental and energy policy in recent years. This study examines recent trends in climate-economy and energy equilibrium research and examines the relationship among the identified key attributes. A bibliometric analysis is used to evaluate scientific publications from the Scopus database that have addressed the relationship between the environment and the economy and have developed climate-economy models. Results show that climate change, emission control, CO_2 emissions are strongly linked with economic and social effects, energy policy, renewable energy resources and energy efficiency. Most recent articles focus on photovoltaic system and electricity, energy utilization, economic analysis and sustainable development.**

Keywords **– Bibliometric analysis; climate-economy; equilibrium; interlinkages**

1. INTRODUCTION

Environment and economy are inseparable. The link between the environment and the economy may not always seem straightforward, but our energy consumption patterns, and the exploitation of environmental resources shape the global economies and societies we live in. The environment is the main source of resources used to create economic value for the overall economy. Natural resources are used as the main raw materials in production, which result in pollution and environmental degradation as a result of the production processes. Negative impacts on the environment, in turn, affect economic performance and long-term development, as a poor state of the environment leads to resources of lower quality and quantity, as well as other negative impacts on human well-being [1].

Climate change is the main cause of weather shocks and deviations from normal outdoor temperatures. Weather shocks directly influence economic output and growth in agriculture and industry. They also affect the economy's total energy demand [2], labour productivity, geopolitical stability, health, security, and social well-being [3]. Kalkuhl & Wenz examined how climate change affects economic output levels and found that global output could decline substantially (by 7–14 %) by 2100 if temperature increases by 3.5 % over that period. The authors find evidence that increases in global surface temperature due to climate change have a negative impact on productivity levels and thus affect economic production outcomes [4]. These findings are also supported by the European Central Bank study, which concludes that the impact of climate change on the EU economy is significant, affecting all major economic

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sectors such as agriculture and fisheries, industry, energy, tourism, and many others. It is estimated that real GDP would decrease by 2–10 % by 2100 if no additional measures are taken to mitigate climate change and temperatures rise [5].

However, some argue that economic growth is necessary to finance investments in infrastructure to mitigate climate change. Therefore, countries should aim for the 'right kind of growth' that does not harm ecosystems while contributing economically [6]. For example, Bowen *et al.* examined changes in economic growth due to climate change adaptation policies and found that some growth policies could create positive synergies and reduce vulnerability to climate change because sufficient investment was made in improving access to capital and promoting labour productivity. The authors emphasise that current growth policies should be carefully designed, including an assessment of climate risk and sufficient provision of investment in climate change adaptation infrastructure [6]. Furthermore, in their study on the interaction between climate and socioeconomic factors, Tachiiri *et al.* argue that climate change not only causes significant economic losses, but also negatively affects numerous social issues such as diseases, migration, labour productivity, and others [7], and therefore negatively impacting the well-being of the society [8].

Climate change poses a major challenge to capitalist-oriented societies to restructure their economies and adapt to low-carbon measures that, at first glance, may not be the most economically viable option. Therefore, climate-economy models have become increasingly important in environmental and energy policy in recent years. Rhodes *et al.* note that the role of energy-economy models in policymaking is increasing because it is critical to develop policies that move toward climate neutrality goals while maintaining stable economic growth and increasing prosperity [9]. Swain and Ranganathan argue that there are both positive and negative interactions between the UN's Sustainable Development Goals (SDGs) and therefore it is important to identify synergies and possible counter-effects between the SDGs [10]. Caglar *et al.* examine the role of energy policy in the context of carbon-income framework and find that environmental quality is positively correlated with trade openness and economic complexity. However, negative environmental impacts are correlated with economic growth factors, natural resource availability, and the establishment of public-private partnerships [11].

Ciarli & Savona emphasise that most of the economic models currently developed exclude the complex nature of the interactions between economic structure and climate change. The authors argue that economic growth factors that lead to structural changes in the economy should be studied in close conjunction with climate change drivers. Excluding climate-economic linkages between different economic and sectoral actors may lead to incorrect projections and outlooks. To build better economic-climate models, representation of evolving complex systems is needed. Modelling should represent systems that are out of equilibrium, which would allow a more detailed study of the dynamic relationship of synergies and contrasting effects [12].

One of the most common techniques for studying the linkages and relationships between climate change and the economy is the use of equilibrium models. Equilibrium models are widely used to study and evaluate the impact of economic development, international trade, climate impact and energy infrastructure policies. Equilibrium models are considered the primary basis for policy evaluation framework [13]. In their review article on equilibrium models for environmental science, Cantele *et al.* argue that while equilibrium models provide the ability to link economic processes to environmental systems, these models are rarely used by environmental scientists because they are unfamiliar with the methodology of the models. This is a major obstacle in environmental science research and hinders opportunities for interdisciplinary research development. Therefore, the application of equilibrium models in the field of energy and climate science should be promoted, which will lead to a significant improvement of models and valuable insights for policy makers [13]. In general, the literature offers a wide range of equilibrium models and there is no consensus among scientists on a single most appropriate method. Recent articles in the scientific literature use equilibrium models such as LIBEMOD, the computable general equilibrium (CGE) model, the GEM-E3 model, the ENV -Linkages model, the REMIND model, and others.

A study by Golombek *et al.* uses two linked models-the LIBEMOD energy equilibrium model and the TIMES-Europe model-to analyse the impact of energy storage and transmission on European carbon neutrality targets of 2050 [14]. Both models – LIBEMOD and TIMES – are linked to produce more explanatory results that would improve decision making by policy makers. First, the LIBEMOD equilibrium model is used to model the projections of future energy demand estimated based on the climate policy targets. The results of the LIBEMOD model are used as the main input data (fuel prices, carbon prices, etc.) for the TIMES Europe model. The combination of both models allows to study how the policy targets affect the overall development pathways [14], [15].

Another widely accepted model used to model the interconnections between the energy sector and the economy is the computable general equilibrium (CGE) model. CGE models allow us to project the economy's potential response to changes in policies, technologies, or other intervention factors. CGE models have been used since the 1970s by international organizations such as the IMF, the World Bank, the OECD, and others [16]. The advantage of CGE models is that they allow us to study the market in depth and examine the impact of various factors on the stability of the economy [16], [17]. A study by Freire-Gonzalez and Ho develops energy–economy–environment dynamic CGE model to study energy and carbon rebound effects from the implementation of different climate and development policies. The authors emphasize that as policy complexity increases, so do rebound effects that impede the achievement of desired goals. Policymakers should take compensatory measures to ensure the achievement of targeted climate goals [18]. Another study uses CGE model to replicate and simulate world’s economy. Babiker included numerous commodities and regions in his CGE model and based the model linkages on production technologies, consumer preferences, international trade and supply of goods, emissions, optimization behaviour and market structure, elasticities. The authors argue that the production and international trade of energy-intensive goods is one of the most important factors that should be included in the development of CGE models to capture real market behaviour and potential carbon leakages between countries [19].

The GEM-E3 model is an extension of the CGE model that includes details on several regions and sectors by considering the relationship between supply, demand, price elasticities of commodities, capital and labour markets, international trade, and investment [20]. The GEM -E3 model is used by the European Commission's Joint Research Centre (JRC) to assess the interactions between environmental, climate and energy policies. The model simultaneously determines the equilibrium in all the sectors, considering labour and capital markets in all the countries [21].

Another modification of the CGE model is the ENV-Linkages model, developed by the OECD and used to study the behaviour and interaction of economic activities and macroeconomic sectors, considering both the energy sources used and international trade [22]. ENV -Linkage's model calculates simultaneous equilibriums in all markets and includes structural considerations. An additional focus is on environmental and climate policy. Therefore, greenhouse gas emissions emitted are separately linked to different economic activities [23].

The REMIND model is an energy equilibrium model that links economic growth to the energy sector. The model can be used by policy makers to analyse the links between economic growth and climate change mitigation goals. A particular focus of the model is on the energy sector and its development pathways, including technological progress and strategic shifts to less carbon-intensive energy sources [24]. A study by Ueckerdt *et al.* develops a REMIND model to analyse progress in variable renewable energy technologies, considering the linkages between the economy, energy, and climate [25].

The purpose of this study is to identify recent trends in climate-economy research and examine the relationships between economic growth and climate change factors and other key attributes identified. In addition, this study aims to examine which model is most commonly used among the available equilibrium models linking the environment and the economy. This study conducts a bibliometric analysis and analyses 344 publications in the field of climate-economy research. Environmental and climate change issues can no longer be separated from economic growth strategies. Therefore, it is important to examine the interrelationships between these two areas in order to develop more effective policies.

2. METHODOLOGY

The aim of the bibliometric analysis is to determine the current state of the art in the research topic under study [26]. It is a quantitative method that measures interlinkages between the main keywords found in the scientific publications of a given research area. Bibliometrics is based on a large number of scientific publications, which are analysed using statistical and network tools integrated into the software [27]. The method allows to identify the key trends in a particular scientific field based on the most recent or most frequently cited academic literature in the research area of the study.

The purpose of this study is to analyse recent advances in climate-economy research by examining in more detail the linkages between climate action and sustainable economic development goals. This study uses the Scopus database, which is one of the main scientific databases in the field of environmental science research [28]. Fig. 1 summarizes all the main steps of research methodology applied in this study.

A total of three queries are used in the analysis, summarized in Table 1. All queries are searched within Title, Abstract, and Keywords of the documents, including abstract, keywords, title, and other sections. The queries are formulated in keywords, which are enclosed in quotation marks to search for the selected phrases rather than individual words. Search tools (AND, OR) are applied to search for publications that contain both search indicators or at least one of them.

First query contains five separate phrases – ‘climate change’ and ‘model’ and ‘economic development’ and ‘emission reduction’ and ‘equilibrium’. This keyword combination is selected to study climate change modelling and economic development linkage with equilibrium. Second query investigates the key attributes of energy-economy-environment model. Third query looks for interlinkages between ‘climate-economy’ (or ‘environment-economy’ or ‘energy-economy’) and ‘equilibrium’.

For each search query, the number of publications in the Scopus database is listed. Only articles and conference proceedings are selected for analysis. Reviews, books, book chapters, or other types of documents are excluded from the analysis to avoid double counting of citations [28]. Only articles and conference papers published between 2000 and 2022 are selected. Data for this study were collected in February–March 2022.

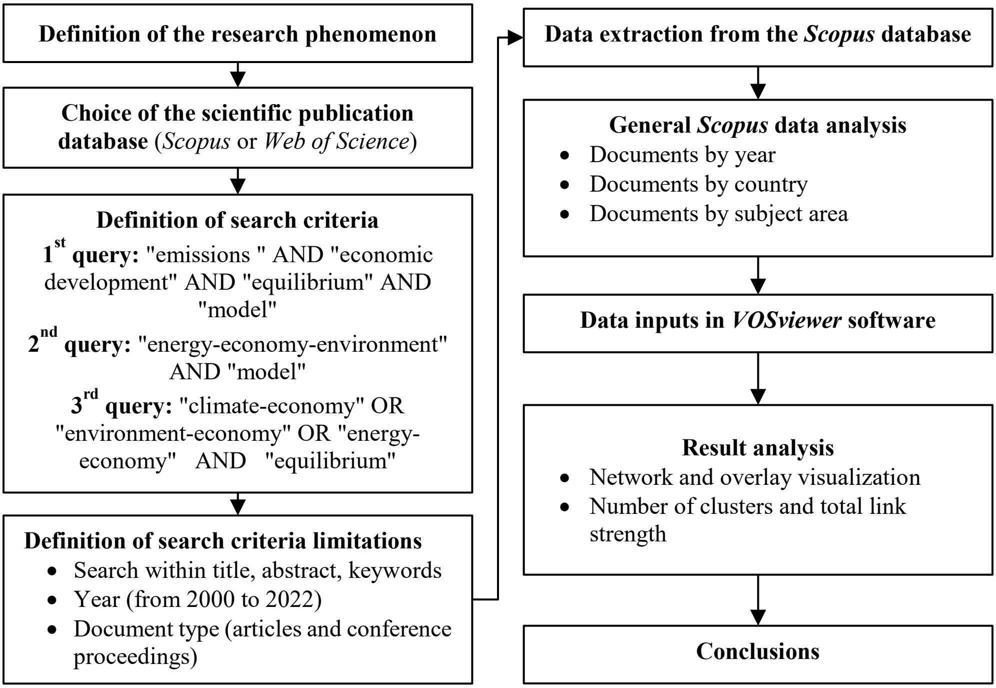

Fig. 1. Main steps of bibliometric research methodology.

TABLE 1. DESCRIPTION OF QUERIES FOR BIBLIOMETRIC ANALYSIS

No.	Topic	Query in Scopus
1	Climate change modelling and economic development link with equilibrium	‘emissions’ AND ‘economic development’ AND ‘equilibrium’ AND ‘model’
2	Energy-economy-environment model	‘energy-economy-environment’ AND ‘model’
3	Climate-economy link with equilibrium	‘climate-economy’ OR ‘environment-economy’ OR ‘energy-economy’ AND ‘equilibrium’

Each publication contains information that is extracted and further used for analysis, such as authors, year, title, research field, country, journal, affiliation, keywords, abstract, and references [28]. Data on the number of annual publications and the distribution of published papers by country and research area were analysed based on search query information from the Scopus database. For more in-depth bibliometric analysis, this study used *VOSviewer* software to visualize the identified links and clusters in the literature and to obtain data summarizing the key information of the articles from the Scopus database. In *VOSviewer* overlay and network visualisation is obtained, in order to visualize interlinkages and identify changes in key research trends by year. The software shows total number of clusters, links, and total link strength.

3. RESULTS

The results for all three queries show that from 2000 to 2022, a total of 344 scientific publications (157 in 1st query, 83 in 2nd query, 104 in 3rd query) and conference proceedings were published linking both climate and economic factors. The overall number of publications for the selected queries gradually increases on annual basis, reaching the highest peak in 2021. Minor decrease in number of publications were observed in 2018 and 2020. While the overall trend in number of publications for queries 1 and 2 is similar and representing gradual increases while for query 3 higher fluctuations are observed. The highest number of publications was observed for query 1 and a lower number of publications for 2nd and 3rd query. This indicates that climate-economy equilibrium models and energy-economy-environment models are less studied than general studies on the relationship between climate change and economic development. However, the number of publications dealing with energy-economy-environment models has increased significantly over the past decade. The climate-economy and energy-economy-environment models have a narrower focus and contain more specific methodology conditions than the methodologies observed in query 1. Fig. 2 illustrates the overall trend in the number of scientific publications published and cited for the queries.

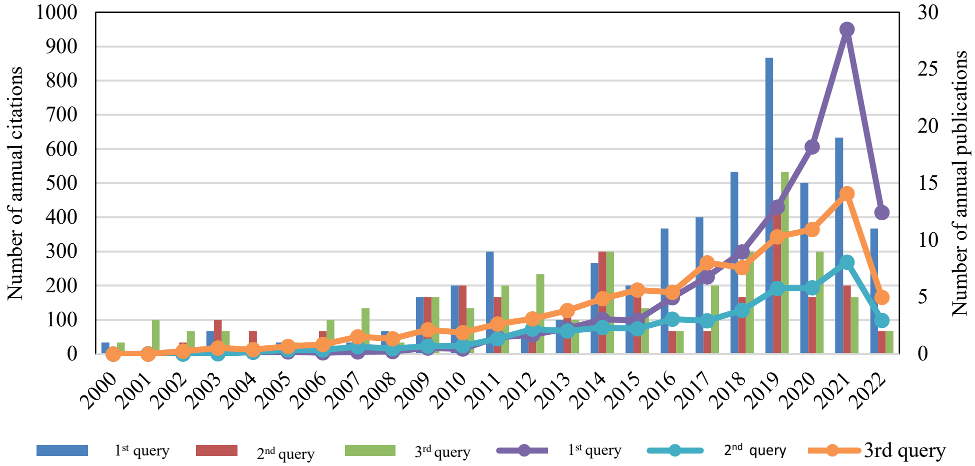

Fig. 2. Overall trend in the number of scientific publications published and cited for the queries.

Similar trend as for number of publications is observed for number of citations of the search queries. The highest total number of citations during the period from 2000 to 2022 was for 1st query (3536 citations), followed by 3rd query which had 3026 citations. 2nd query had significantly lower total number of citations (1530 citations) than 1st and 3rd query. Both the number of publications and the number of citations show that the keyword combination 'energy-economy-environment' modelling is less frequent than more general searches for climate-economy-modelling links. In general, a significant gradual increase in the number of scientific publications published and cited each year can be observed starting from 2011. Following the global financial crisis in the last decade, climate change issues became more prominent and more stringent climate and energy policies were adopted, which significantly increased the urgency of studying the impact of these policies on overall economic development. As a result, research using the climate-economy model increased, reaching its highest level in 2021. Rising number of climate-economy research in the past decade is also explained by the establishment of international energy and climate policy such as the Paris Agreement in 2016 [29]. Following the establishment of stringent climate change mitigation targets at the global level, an increasing number of scientific publications in the field of climate policy have been published using decision support models [30].

Fig. 3 illustrates the general trend in research areas for all queries. Environmental science (29 %) was the top research area for all queries. Followed by energy (19 %) and engineering (13 %). Economics, econometrics, and finance accounted for only 9 % of the total number of researches. This suggests that there is not yet a strong synergy between the fields of environmental science, energy, engineering, and economics, and multidisciplinary of these fields should be encouraged. The current research communities are fragmented, so conceptual bridges should be built between the fields of environmental engineering and climate economics to strengthen interdisciplinarity [31].

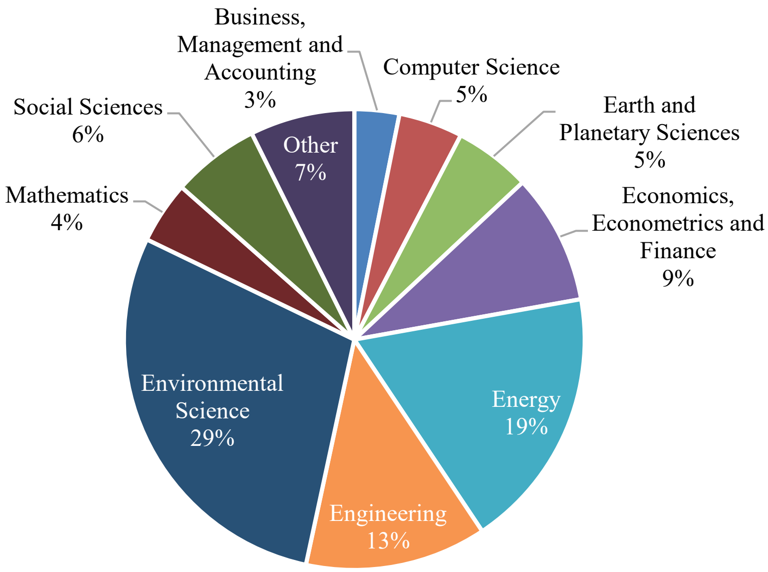

Fig. 3. Overall trend in the subject area of publications for all queries.

Fig. 4 illustrates the total number of publications published for all queries from 2000 to 2022 by country. The results show that China is the absolute leader in climate-economy linkages research, with a total of 180 publications during the period, followed by the United States (41 publications), the United Kingdom (26 publications), and Germany (19 publications). China is the world's second-largest economy and has not only experienced some of the fastest economic growth in the last decade, but has also faced increasing international pressure to meet climate change targets that include massive reductions in energy consumption and greenhouse gas emissions [32]. This could be a possible explanation for the fact that China is an absolute leader in climate-economy research, as measured by published scientific papers.

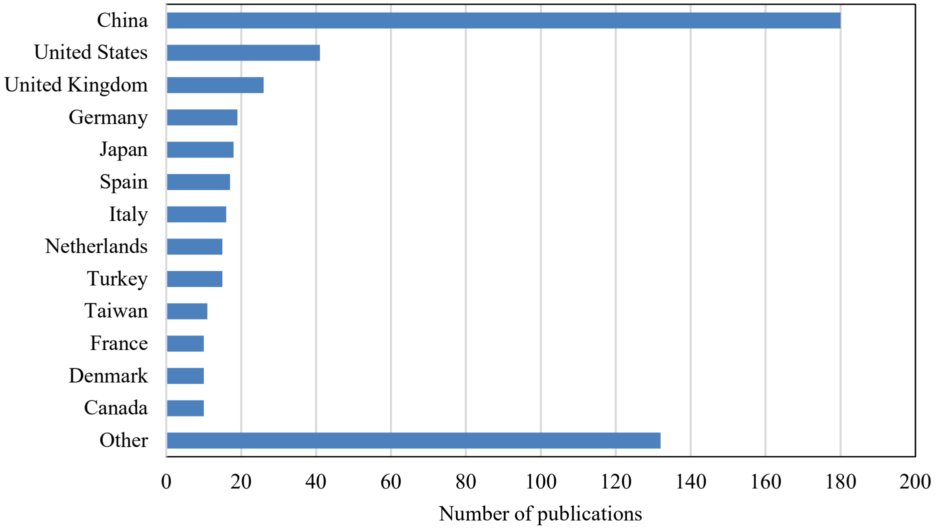

Fig. 4. Overall trend in the countries of publications for all queries.

Furthermore, more in-depth results on the main linkages were obtained from the bibliometric analysis using the *VOSviewer* software. Fig. 5 shows the keyword co-occurrence for the 1st query with a threshold of at least 10 occurrences. The analysis of keyword co-occurrence for 1st query identified a total of 1474 keywords, but only 47 of them met the threshold of 10 occurrences. Economic development with 104 occurrences was the most commonly used keywords in the publications under 1st query. Carbon emission (64 occurrences), carbon dioxide (60 occurrences), China (52 occurrences), emission control (46 occurrences), economics (46 occurrences), and environmental economics (41 occurrences) were other keywords with the highest number of occurrences. The keywords in the 1st query formed a total of 3 main clusters, each dominated by the keyword with the highest number of cooccurrences and the highest link strength: (1) economic development, (2) emission control, (3) China.

In the cluster of economic development strong links are found between the keywords – carbon emission and economic growth. Moreover, economic development cluster includes strong links with numerous energy and climate keywords such as energy use and conservation, alternative energy, environmental pollution which also have occurrences with economic keywords such as investments, policy, and urbanization.

The emission control cluster has strong links to the keywords – economics, economic and social effects, climate change, environmental protection, sustainable development. China has a high number of links and a high co-occurrence due to the highest number of publications was published in China. Environmental policy, gross domestic product and gross national product, carbon footprint, air pollution, energy consumption are the main keywords associated with China. This indicates that China attaches more importance to the study of the impact of climate change on the gross national product.

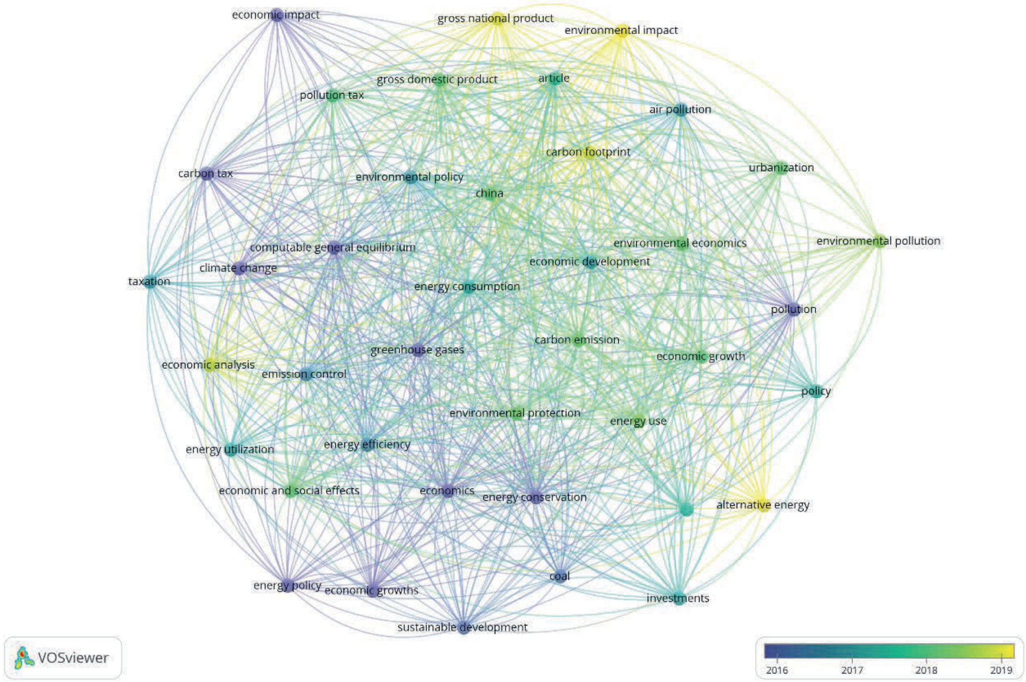

Fig. 5. Keyword co-occurrence for 1st query with a threshold of at least 10 occurrences.

The overall keyword co-occurrence analysis for 1st query highlights also a computable general equilibrium (CGE) model that is one of the most commonly applied models to study economic equilibrium considering the impacts from energy sector. In addition to CGE model, co-integration analysis also appears to have 32 links with 10 co-occurrences in the 1st query. CGE models are used in climate economics studies to analyse the economic impacts of adopting more stringent climate policies and to assess the costs of mitigating climate change [33].

Most recent publications contain keywords – alternative energy, economic analysis, carbon footprint, environmental impact, CO_2 emissions. These findings indicate that in recent years higher attention is paid on studying renewable energy resources and created environmental impact. However, older publications were more focused on studying coal, carbon taxation and its economic effects. Carbon-tax has been most widely used market-based instrument in climate policy [34]. This show that there has been a shifting trend in research of fossil fuels to more active and advanced research on alternative energy resources. Carbon emissions has been a central element in the studies across different time periods.

Compared to the 1st query, which focused on finding general links and equilibrium between economic development and emissions, the 2nd query looks specifically for keywords found in scientific publications that mention or use the energy-economy-environment model. Therefore, the total number of keywords for the 2nd query is significantly lower than for the 1st query. A total of 889 keywords were found, 13 of which were selected for further analysis because they met the threshold of at least 10 occurrences. Fig. 6 illustrate the keyword co-occurrence and interlinkages for 2nd query.

Analysis of the occurrence of keywords for the 2nd query revealed 3 main clusters. The first cluster focuses on economic factors determined by more efficient energy use and optimization of both economic and energy resources. Economics (with 26 occurrences) is the main keyword of the first cluster, which is linked to the keyword's energy utilization, energy efficiency and optimization. The second cluster contains the most keywords and links and focuses on CO_2 emissions (with three keywords – carbon emission, carbon dioxide, and emission control) and its impact on sustainable development. The second cluster also contains the keyword environmental economics (with 15 occurrences and a total link strength of 35), which links environmental science to economics and finance. The third cluster connects the first and second clusters by forming three main keywords – climate change, energy policy, and environmental policy.

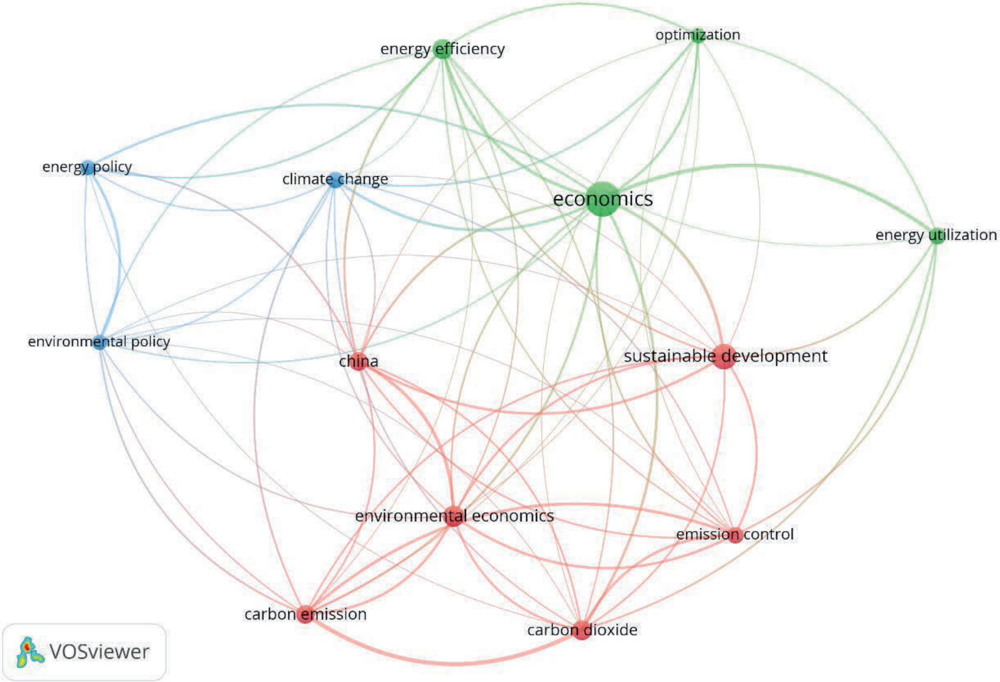

Fig. 6. Keyword co-occurrence for 2nd query with a threshold of at least 10 occurrences.

The overlay visualization of the 2nd query shows that recent publications are more concerned with sustainable development and energy policy issues, while older publications are more focused on optimization and environmental policy issues. The results of the bibliometric analysis show that there has been a shift from focusing only on environmental policy to more attention to studying and strengthening energy policy with a strong presence of sustainable development factors.

Fig. 7 illustrate the keyword co-occurrence and interlinkages for 3rd query. For the 3rd query, a total of 1186 keyword occurrences were found, of which only 18 keywords met the threshold of at least 10 occurrences. However, since the computable general equilibrium was identified in three keyword positions, two of them were excluded to rule out double counting. Therefore, the 3rd query contained a total of 16 keywords that met the threshold of at least 10 occurrences.

Economics (with 26 occurrences) and climate change (with 23 occurrences) were the two keywords with the highest number of co-occurrences and total link strength. These keywords were followed by other keywords explaining climate-economy modelling such as emission control (with 20 occurrences), computable general equilibrium model (with 19 occurrences), environmental economics (with 17 occurrences), and carbon dioxide (with 17 occurrences).

In general, 3rd query form 2 main clusters. One is represented by the main keywords – economics and climate change which form strong links with environmental policy, climate models, computable general equilibrium, investments, energy policy, and economic and social effects. Other is determined by three main keywords – emission control, carbon dioxide, and environmental economics which from links with energy utilization, energy efficiency, carbon, carbon emission, and China.

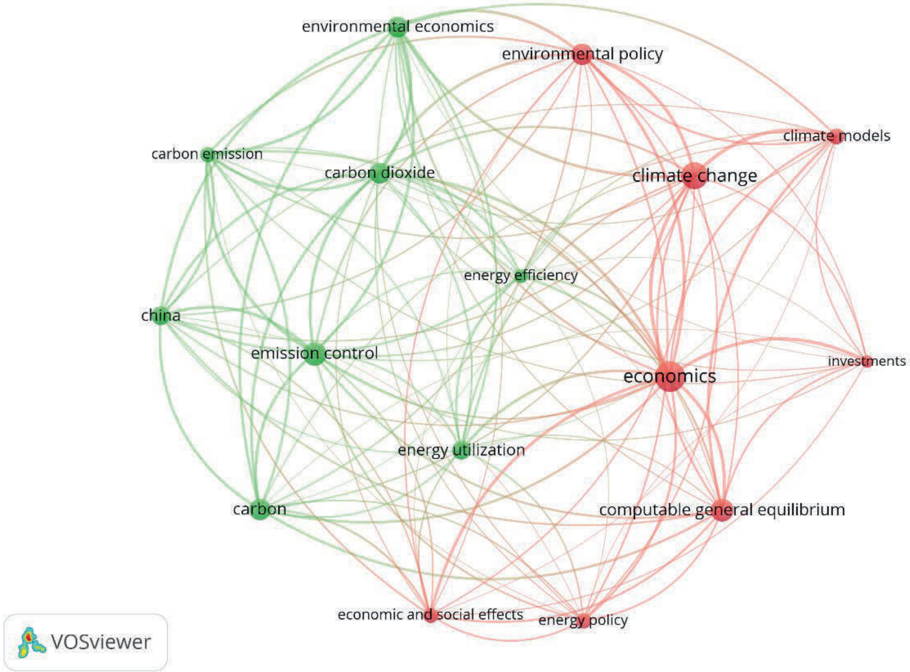

Fig. 7. Keyword co-occurrence for 3rd query with a threshold of at least 10 occurrences.

A bibliometric overlay analysis for the 3rd query shows that the most recent publications use a computable general equilibrium to model the interactions between climate and the economy. In addition, economic and social effects predominate in the most recent publications. Recent studies point to the social costs of rising carbon emissions due to climate change, which are reflected in society's overall welfare losses [35]. These results suggest that environmental economics research is placing more emphasis on a multidisciplinary research approach that considers all aspects of sustainable development – economic, environmental, and social.

4. CONCLUSION

In general, bibliometric analysis is a useful method that helps to identify the most frequently used keywords in a large number of scientific publications on the research area of the studied topic. The *VOSviewer* software makes it possible to visualise the main interlinkages and relationships between the most important keywords, thus highlighting the key factors emphasised in the specific research area.

In this study, a bibliometric analysis was conducted to examine what relationships exist between climate and economy, and what models are used in research to examine these interlinkages. In total three search queries were investigated. First query studied the climate change modelling and economic development link with equilibrium, where equilibrium is a state that represents the perfect balance between these two pillars. The results from the first query show that there is a shift from a focus on researching fossil energy resources to researching alternative energies and their impact on the environment and the gross national product. Older studies have emphasised the carbon tax as one of the most important energy and environmental policy research elements. However, more recent studies emphasise energy conservation and energy efficiency and their impact on both emission reduction and economic goals.

The second query examined the main keywords identified between ‘energy-economy-environment’ and ‘model.’ The results showed that there are strong links between economy, climate change and sustainable development, with emission control and optimization being the main containing elements between these interlinkages.

The third query specifically examined the link between climate-economy and equilibrium and concluded that the computable general equilibrium (CGE) model is the most widely used modelling technique among research examining the relationships between carbon emission reduction targets and their effects on the overall economy.

In general, the results indicate that there is an increasing trend in climate-economy research and the annual number of published scientific papers and citations is gradually increasing, with the most rapid growth in the last decade. China is the absolute leader in climate-economy research in terms of the number of publications in the period from 2000 to 2022, followed by the United States and United Kingdom. In general, the summary statistics of the research fields for all the publications of the queries showed that there is not yet a strong synergy between the fields of environmental science, energy, engineering, and economics, and multidisciplinary of these fields should be encouraged.

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Currently, Kristiāna works as a Sustainability Manager at Swedbank's Local Asset Management Company, where she is responsible for integrating and monitoring sustainability practices within pension fund investment processes.