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Analyzing Challenges to the Low-Carbon Energy Transition in the EU

DOCTORAL DISSERTATION

Social Sciences,
Economics (S 004)

VILNIUS 2024

The dissertation was prepared between 2020 and 2024 at the Institute of Social Sciences and Applied Informatics, Kaunas faculty.
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Mahyar Kamali Saraji

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INTRODUCTION

The dissertation identifies challenges and categorizes them into different pillars as an inclusive framework. Indicators are also identified in the present dissertation to measure the EU's performance. Considering the dynamic interactions between challenges, the present dissertation maps the interactions and analyses them under various assumptions for a case study. Furthermore, the dissertation finds suitable locations for building solar farms vital for a prosperous low-carbon transition. The dissertation applies various novel methods to reach its goals in different stages. The dissertation results were presented in four published articles and at four international scientific conferences.

Relevance and novelty of the topic

The energy sector significantly contributes to greenhouse gas (GHG) emissions. In other words, GHG emissions impacts on global warming and climate change have become one of the most critical global issues(Huang & Liu, 2021). As a result, various global and local agreements have been implemented to focus on achieving low (or zero) carbon energy, such as the Paris Agreement (Sorman, García-Muros, Pizarro-Irizar, & Gonzalez-Eguino, 2020). Despite the international agreements, adopting energy policies faces various challenges(Nuru, Rhoades, & Sovacool, 2022). Addressing challenges and controlling global warming require collaboration on many levels (Boulogiorgou & Ktenidis, 2020). Academics are vital in studying and facilitating the challenges (Meha, Pfeifer, Sahiti, Schneider, & Duić, 2021).

Moreover, transition governance is a complex process that facilitates the transition (Markard & Rosenbloom, 2020). This process requires gradual reform, especially in authoritarian countries, where rules often hinder the transitions(Goldthau & Westphal, 2019). Successful transition requires adopting innovative technologies and adjusting regulations (Rosenbloom, Meadowcroft, Sheppard, Burch, & Williams, 2018). In addition to societal and policy changes, infrastructure renovation is essential for the energy transition. Therefore, evaluating countries' performance in coping with the challenges is a multicriteria decision-making process(Guler, Çelebi, & Nathwani, 2018).

Furthermore, scenario planning is crucial in developing a low-carbon energy system. It involves understanding the dynamic interaction between technological innovation, economic factors, and regulatory changes(Van

Vuuren, Kok, Girod, Lucas, & de Vries, 2012). By proposing an inclusive framework, stakeholders can develop multiple scenarios based on different assumptions(Sovacool, Hook, Martiskainen, & Baker, 2019). scenario planning enables a detailed analysis of potential outcomes, showing how prioritizing specific challenges might impact the overall result(Cherp, Vinichenko, Jewell, Brutschin, & Sovacool, 2018). It equips decision-makers with a robust tool to visualize current and future possibilities in the energy system(Amer, Daim, & Jetter, 2013). Rigorous scientific research and scenario planning offer deeper insights into the pathways toward achieving a sustainable and resilient energy future (Geels, Berkhout, & Van Vuuren, 2016).

Additionally, expanding low-carbon or zero-carbon energy sources is crucial to facilitate the reduction of greenhouse gas emissions(Kuşkaya et al., 2023). However, the limited availability of land significantly challenges the transition(Borras Jr & Franco, 2013). Consequently, it is essential to identify optimal sites for the construction of solar farms(Wang, Dang, & Wang, 2022). This idea entails evaluating various factors that influence the suitability of locations for establishing solar farms. Assessing the efficiency of these locations and selecting the most suitable site for solar farm development is crucial(Stock & Birkenholtz, 2021). Previous studies showed that solar irradiance, land availability, environmental impact, proximity to existing infrastructure, and socioeconomic conditions impact the selection of solar farms(Wang, Chung, Wibowo, Dang, & Nguyen, 2023). Therefore, understanding these factors is crucial for decision-making, the efficient use of resources, and ensuring that solar farms are both economically viable and environmentally sustainable (Wang, Dang, & Bayer, 2021).

Contributions to economics

A transition towards low-carbon energy is an economically intensive process with regulation changes, including carbon pricing and standards. Economic analysis of such governance models may help decision-makers compare the costs and benefits of such regulatory changes.

This study offers an economic tool for ranking countries based on their effectiveness in addressing these challenges, which can inform future investment decisions and policy reforms within the EU.

Economists can apply the proposed assessment frameworks in the present dissertation to evaluate factors impacting solar farm location selection; it helps better allocate resources and long-term economic sustainability.

Research problem

There is a need for an inclusive framework of the challenges. This framework should identify the barriers and issues and enhance understanding of these challenges. Also, a comprehensive assessment framework encompassing relevant challenges is required. Such an assessment framework is necessary for countries to accurately evaluate their performance in addressing these challenges. It could help decision-makers to develop effective strategies for progressing towards a greener future.

Furthermore, adopting low-carbon energies requires significant initial investments, so a broad picture of the transition is crucial. Decision-makers must understand all aspects of transitions, as moving toward a low-carbon economy will burden both governments and societies. On top of that, economic factors should be discussed along with other factors, such as the labor market in a dynamic environment, to see how their interactions would impact economic policies, such as carbon pricing or subsidies. Overcoming economic challenges requires coordinated action from governments, private investors, and international institutions; therefore, an inclusive framework is needed to consider all stakeholders' interests, which could be theoretically and practically used in all stages.

Additionally, there is a need for an appropriate framework for scenario planning. Countries must simulate different scenarios based on their unique priorities and resources to set realistic targets. However, existing literature does not provide a framework that includes all challenges and their interactions. Furthermore, the current literature needs step-by-step guidelines for evaluating the factors impacting the suitability of potential sites for building solar farms. As a result, developing a detailed framework for site suitability analysis is essential to facilitate solar farm development.

Research aims and objectives

The dissertation aims to investigate the challenges to the low-carbon energy transition and monitor the EU's performance in dealing with them. The following objectives should be reached to achieve the aim of the dissertation:

1. The present study establishes a comprehensive framework for understanding the complex challenges associated with the shift to low-carbon energy. It integrates social, environmental, institutional, and economic elements to provide a holistic view of the obstacles to this transition and the strategies to overcome them. It also analyzes

various features of studies, including methodologies, future research directions, gaps, and study objectives. Its ultimate goal is to improve the understanding and management of these challenges and assist policymakers and stakeholders in formulating effective strategies.

2. The present study develops an assessment framework to address these challenges through an integrated method in fuzzy environments. It evaluates and ranks countries' performances by determining identified indicators' subjective and objective weights.
3. The study uses scenario planning to assess the performance of Lithuania's energy system by examining three different scenarios. It develops a scenario to prioritize public welfare, focusing on indicators closely linked to public interests, such as subsidies and public engagement measures. It develops a scenario highlighting technological advancement and innovation, fully activating innovation, reformation, and technical standards indicators. It develops a scenario to balance public welfare and technological advancement by moderately activating public engagement and investment indicators. It evaluates each scenario using a novel MCDM method to identify the most effective strategy.
4. The study establishes a comprehensive framework for assessing the optimal site selection. It seeks to overcome the limitations of previous research by considering a more comprehensive range of factors that influence site selection. The study considers economic and social factors crucial in identifying the most suitable locations. It ensures a balanced decision-making process considering environmental preservation, economic prosperity, social well-being, and technological progress.

Research methodology

The article employs the integrated PSALSAR technique, which combines the PRISMA and SALSA frameworks for a systematic literature review. The PRISMA protocol is used to enhance transparency and reproducibility, and the study's scope is defined using the PICOC framework (Population, Intervention, Comparison, Outcome, and Context). Furthermore, The study uses the Fermatean fuzzy set-based Stepwise Weight Assessment Ratio Analysis (SWARA) method to determine the subjective importance of each challenge. Additionally, the method based on the Removal Effects of Criteria (MEREC) is used to calculate the objective weight of the indicators. The Technique for Order of Preference by Similarity to Ideal Solution

(TOPSIS) is then utilized to rank alternatives. Moreover, The research uses advanced methodologies by combining Intuitionistic Fuzzy Cognitive Maps (IFCM) and TOPSIS for scenario planning, simulation, and ranking. Also, the dissertation utilizes a unique integrated method that combines DEA and the CRITIC-TOPSIS approach to improve the selection process for solar farm sites.

Defending statements

- Technical challenges are not the only ones.
- A just energy transition ensures an equitable and inclusive shift towards cleaner energy sources.
- Land use is one of the most critical challenges due to its significant impact on the environment and society.
- It is essential to involve society in scenario planning.
- Challenges are interconnected, and dealing with a specific challenge might impact others.
- Climate factors are crucial in determining the suitability of locations for building solar farms, but they are not the only considerations.

Key results of research

- An inclusive framework of challenges and a review of methods tackling them.
- Illustrating the distribution of studies based on various features.
- Providing a research agenda based on future research directions.
- To offer policy recommendations. It is crucial to stress the importance of grounding policy recommendations in evidence-based insights.
- Proposing and applying integrated methods to assess the performance of EU countries in addressing challenges.
- Mapping the interactions between the challenges using IFCM
- Developing scenarios to evaluate the energy system's performance in Lithuania, the case study, under different assumptions.
- Ranking the developed scenarios and find the best one.
- Proposing a new two-stage approach for selecting solar farm sites.
- Applying the proposed approach in a practical application to find the best location.

Research structure

Chapter 1. This chapter presents the first article connecting to the dissertation in which challenges were identified. In this chapter, the challenges of low carbon were identified as the theoretical of the dissertation. A research agenda is also proposed based on future recommendations from previous research. The challenges also are explained in detail and supported by recent references.

Chapter 2. This chapter presents the second article, which connects to the dissertation, in which a novel multicriteria decision-making method was used to evaluate performances. More specifically, countries have been ranked in this chapter using available data for 2015 and 2020. The results for two years were compared, and sensitivity analyses were done to check the reliability of the outputs. On top of that, the results are presented in the form of tables and figures alongside an in-depth discussion.

Chapter 3. This chapter presents the third article, which connects to the dissertation, in which fuzzy cognitive maps were used to investigate challenges dynamically and develop scenarios for Lithuania's energy system. Experts were asked to map the interactions between the identified challenges, and then the individual mind maps were aggregated. Three scenarios were developed under various assumptions to be used as initial values in the model. The scenario planning results were ranked using the MCDM method to find the most suitable scenario.

Chapter 4. This chapter presents the fourth article, which connects to the dissertation, in which a two-stage novel method was used to evaluate the efficiency of the potential places for building solar farms in Lithuania and then rank the potential and efficient places. In the first stage, the most efficient sites for building solar farms in the Baltic were found. Then, the potential places in Lithuania were analyzed using the MCDM method according to various criteria. On top of that, the results obtained were compared with international reports to check their reliability.

CHALLENGES TO THE LOW CARBON ENERGY TRANSITION: A SYSTEMATIC LITERATURE REVIEW AND RESEARCH AGENDA

This chapter presents the first article published in *Energy Strategy Reviews*. In the present article, the challenges of low carbon were identified and used as the foundation of the articles connected to the present dissertation. Besides, applied research methods in the literature on the same topic were reviewed, and a comprehensive research agenda was proposed.

This chapter will investigate the first research statement: A low-carbon energy transition is not only a technical transition but a socio-technical transition, facing various social, environmental, economic, institutional, and technical challenges. Also, this chapter can be considered as a theoretical part of the dissertation. This chapter represents the first step of the dissertation by identifying challenges.

A comprehensive literature review from 2006 to 2023 was conducted using the PSALSAR protocol to assess Scopus and Web of Science publications. The study delineates 17 challenges encompassing social, economic, environmental, technical, and institutional aspects. It also examines the methodologies proposed in research publications to tackle these challenges, outlines prevailing trends, and offers policy recommendations. The aim is to provide decision-makers and researchers with a robust framework of challenges and a research agenda.

The research background of the article emphasizes the energy sector's critical role in GHG emissions. Transitioning to a low-carbon system is crucial for addressing transition issues highlighted by international agreements like the Paris Agreement. The need for renewable and sustainable energy alternatives is driven by increasing energy demands, reducing fossil fuel reserves, and reducing CO2 emissions. Despite international commitments, energy policies have faced obstacles to achieving effective carbon reductions; therefore, adopting renewables is necessary to mitigate climate change. However, significant obstacles remain, requiring comprehensive research to inform effective solutions.

The research questions in the article are as follows:

What barriers and challenges occur when implementing the shift to low-carbon energy?

How do we tackle the obstacles, and what approaches are used?

What are the primary areas for more research in this context?

The article employs the integrated PSALSAR technique, which combines the PRISMA and SALSA frameworks for a systematic literature review. The PRISMA protocol is used to enhance transparency and reproducibility, and the study's scope is defined using the PICOC framework. The key research questions focus on identifying challenges, methodologies used to address these challenges, and research gaps. A comprehensive search strategy with keywords related to the low-carbon energy transition is implemented. During the appraisal phase, the PRISMA protocol selects eligible studies based on inclusion and exclusion criteria.

The synthesis phase categorizes info based on publication year, journals, case study locations, research gaps, aims, results, and methodologies. The categorized data is scrutinized in the analysis phase to answer the core research questions. The report phase summarizes the analysis results using the PRISMA statement's 27-item checklist, ensuring a structured and comprehensive presentation of the literature review outcomes. Figure 1.1. shows the steps of PSALSAR.

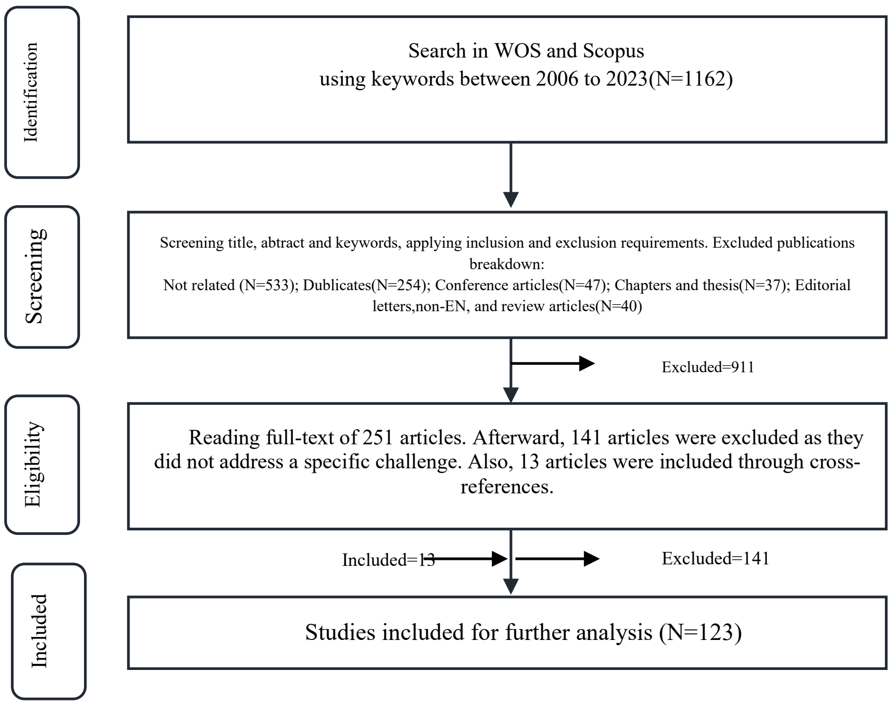

Figure 1.1. Research information flow

The study outlined 17 critical challenges. Social challenges include public acceptance, awareness, and public behavior. Economic challenges encompass high initial costs, financial risks, and the need for substantial investments in new infrastructure. Environmental challenges involve land use conflicts, resource availability, and ecological impacts of renewable energy projects. Technical challenges are related to the reliability and efficiency of green technologies. Institutional challenges include regulatory frameworks, policy inconsistencies, and coordination among multiple stakeholders. The study also explored the methodologies used to address these challenges. It discussed qualitative approaches like interviews and case studies and quantitative techniques such as modeling and simulation. Hybrid methods that combine qualitative and quantitative approaches are also noted. The review emphasizes the need for more integrated and holistic approaches. Stakeholder engagement, interdisciplinary collaboration, and adaptive policy frameworks are crucial for progress. Figure 1.2. shows the framework of challenges.

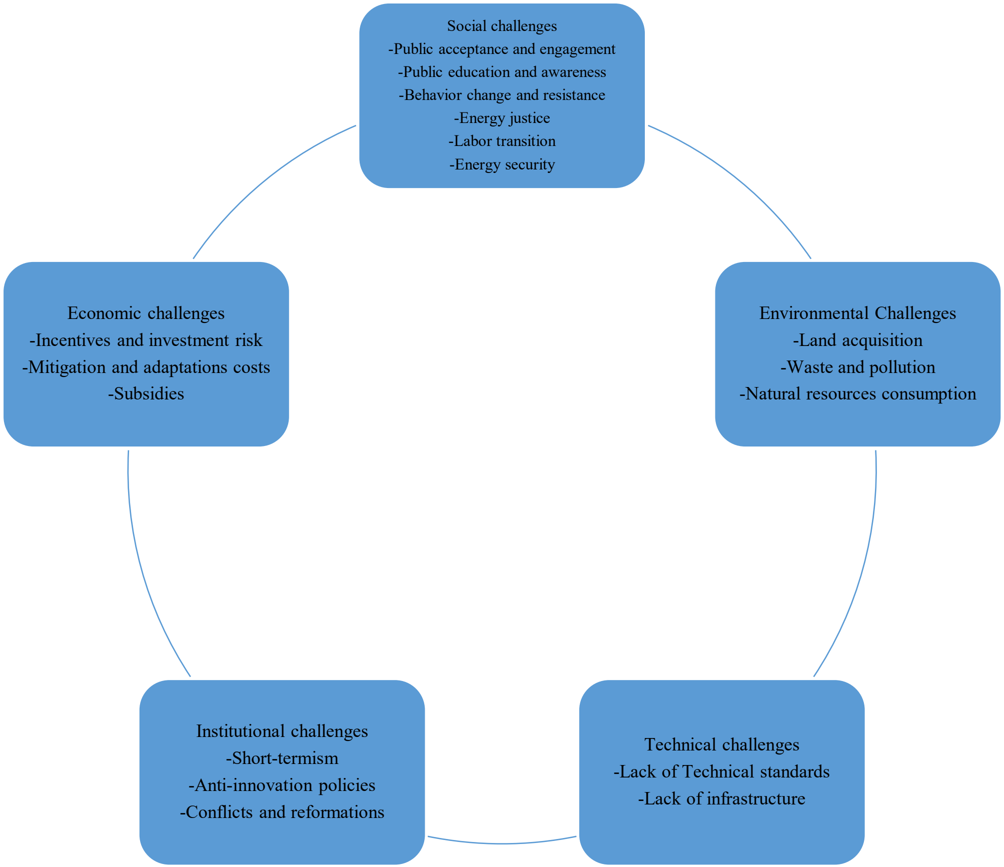

Figure 1.2. The framework of challenges

The results indicated that addressing these challenges requires an integrated approach considering the interconnection between pillars. Although significant progress has been made in renewable energy technologies, there is still a need to improve public awareness and acceptance. The study provided several policy recommendations, including developing adaptive regulatory frameworks that can evolve with technological advancements and changing socioeconomic conditions. It also highlighted the importance of targeted financial incentives to reduce the high initial costs of renewable energy projects. Overall, the article provided a detailed and systematic analysis of the challenges and offered a clear agenda for future research.

A NOVEL MULTICRITERIA ASSESSMENT FRAMEWORK FOR EVALUATING THE PERFORMANCE OF THE EU IN DEALING WITH CHALLENGES OF THE LOW-CARBON ENERGY TRANSITION: AN INTEGRATED FERMATEAN FUZZY APPROACH

This chapter presents the second article published in *Sustainable Environment Research*. In the present article, the performance of the EU in coping with the identified challenges in Chapter 1 was studied using a novel MCDM method.

This chapter will investigate the second and third research statements: A just energy transition is essential as it ensures that the shift towards cleaner energy sources is equitable and inclusive; land use is one of the most critical challenges due to its significant impact on the transition. The chapter can be considered as some part of the methodological part of the dissertation and its applications for solving real-life problems. The results of this chapter will be used as the basis of the third and fourth chapters, and Lithuania's rank will be found in this chapter. Lithuania is the case study in chapters three and four.

The present study develops an assessment framework for evaluating performances. The study uses the Fermatean SWARA to determine the subjective importance of each challenge. Additionally, MEREC calculated objective weights. TOPSIS is then utilized to rank EU countries in 2015 and 2020.

The research background emphasizes the EU's commitment to shifting towards low-carbon energy systems. This commitment directly responds to the global climate crisis and the pursuit of sustainability. The EU is dedicated to reducing harmful emissions and increasing the use of renewables in line with the goals outlined in the Paris Agreement. However, transitioning to low-carbon energy is a complex process with various challenges. Addressing these challenges is crucial to successfully transitioning to a sustainable energy system within the EU.

This study aims to comprehensively identify these challenges and evaluate the effectiveness of EU countries in addressing them to meet their goals.

The main focus of this study is to address the research questions within the EU. The key questions include:

- What are the obstacles to adopting across the EU?
- How can the performance of EU countries in addressing these challenges be effectively measured and evaluated?

- What are the key elements influencing the success or failure of low-carbon energy policies and initiatives in different EU countries?
- How can integrating MCDM methods like SWARA and MEREC enhance the reliability and objectivity of performance assessments in this context?

The present research used a comprehensive MCDM framework to evaluate how well EU countries are transitioning to low-carbon energy systems. This framework integrated SWARA, MEREC, and TOPSIS methods. Firstly, SWARA determines the subjective weight of challenges. After the subjective assessment, the MEREC method calculates the objective weights of the indicators associated with each challenge. The integration of these MCDM methods ensures a reliable assessment of the challenges and performances in the EU's transition.

The research results show that energy justice in the EU is the main challenge. Energy justice includes distributive, procedural, restorative, and recognition justice. Despite its importance, the energy sector has historically not been adequately evaluated in delivering justice, leading to numerous environmental and climate issues.

The findings also highlight that ensuring equitable access to affordable and clean energy is essential, especially for vulnerable and low-income communities. On the economic front, mitigation and adaptation costs emerged as the most influential challenges. Effective mitigation can reduce the long-term need for adaptation.

The results also indicated the importance of significant investment in fostering innovative low-carbon technologies and implementing renewable energy infrastructure. This investment is crucial for increasing the share of renewables.

The research findings provide detailed insights into the performance rankings of EU countries regarding their low-carbon energy transition. Germany and the Netherlands performed exceptionally well, securing the first and second ranks in 2020.

Denmark consistently maintained its third position, indicating steady progress in addressing the challenges. Poland had the worst performance, ranking 22nd in 2015 and slipping further to 23rd in 2020, primarily due to its underdeveloped infrastructure for low-carbon technologies.

Slovenia performed significantly better, ranking 8th in both years. Spain showed the most robust improvement, advancing from 21st place in 2015 to 11th in 2020, primarily due to its effective management of public resistance and increased investments.

Italy also improved its ranking from 19th in 2015 to 14th in 2020. In contrast, Portugal's performance declined from 12th to 17th over the same period, highlighting the need for a more comprehensive approach to addressing various challenges beyond public resistance.

The overall rankings suggest that while some countries have made significant progress, there is room for improvement across the EU to meet the identified challenges effectively. Figure 2.1. shows the countries' rank according to their performance.

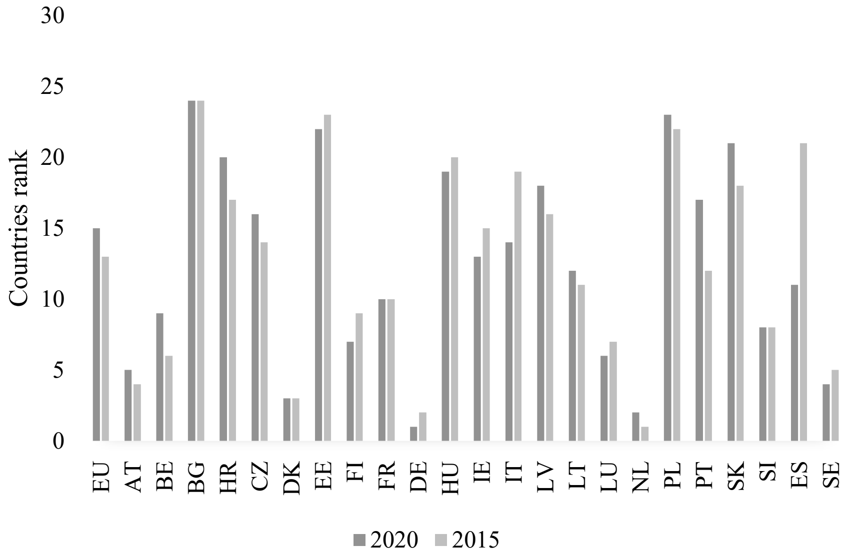

Figure 2.1. Ranking results

This study used advanced MCDM methods in a fuzzy logic framework to evaluate the capacities of EU countries to cope with challenges. It shows significant differences among member states across social, economic, environmental, and institutional dimensions. Countries with robust policy frameworks, high public engagement, and substantial investments. This result aligns with existing literature emphasizing the role of energy policies. The study highlighted the role of energy justice in advancing the EU's low-carbon agenda and addressing social barriers that hinder public involvement. It also advocated a balanced approach to optimize resource use and system resilience.

AN ANALYSIS OF CHALLENGES TO THE LOW-CARBON ENERGY TRANSITION TOWARD SUSTAINABLE ENERGY DEVELOPMENT USING AN IFCM-TOPSIS APPROACH: A CASE STUDY

This chapter presents the third article published in the *Journal of Innovation & Knowledge*. In the present article, some scenarios for moving toward a low-carbon energy system in Lithuania are analyzed using cognitive maps according to the identified challenges in Chapter 1 and identified indicators in Chapter 2.

This chapter will investigate the fourth and fifth research statements: It is essential to involve society in scenario planning for a low-carbon energy future; challenges are interconnected, and dealing with a specific challenge might impact others. The chapter can be considered as some part of the methodological part of the dissertation and its applications for developing scenarios and simulating them under real-life assumptions. The results of this chapter were widely used for the main conclusions of the dissertation as developed scenarios were accurately designed for the case study and analyzed based on available data for Lithuania.

The research uses advanced methodologies by integrating IFCM and TOPSIS for scenario planning. The main goal is identifying and analyzing challenges dynamically. This approach involves creating scenarios based on different assumptions to evaluate the energy system's performance under various conditions. Subsequently, TOPSIS ranks these scenarios. This approach assists in minimizing risks, promoting innovation, and developing resilient energy systems by identifying best scenarios and facilitating policy implementation. Scenario planning offers an inclusive approach to energy transition, ensuring informed and transparent decision-making.

Using scenario planning to address these challenges is essential since the method allows policymakers to explore future possibilities and outcomes under various assumptions. Lithuania's high reliance on energy imports and the requirement for substantial investments highlights the need for scenario planning. Therefore, Lithuania can develop effective policies supporting sustainable development and ensure a smooth transition.

The research aims to answer several essential questions:

- How can IFCM be used to model uncertainties and hesitations in the relationships between different factors affecting the energy transition?

- How can scenario planning help understand the potential outcomes of policy decisions and strategic actions?
- What are the most effective strategies for overcoming the identified challenges and achieving Lithuania's sustainable low-carbon energy system?

This study uses an integrated approach that combines IFCM and TOPSIS to tackle the challenges in Lithuania. The methodology begins with a thorough literature review to identify critical challenges and indicators. Experts are then consulted to create their mind maps using intuitionistic fuzzy sets. These individual maps are aggregated into one fuzzy cognitive map using FCMapper.

Subsequently, scenario planning explores different future pathways for Lithuania's energy transition. Lithuania's performance under these scenarios is assessed using IFCM equations. TOPSIS is then employed to rank these scenarios. Figure 3.1. shows scenarios' initial values.

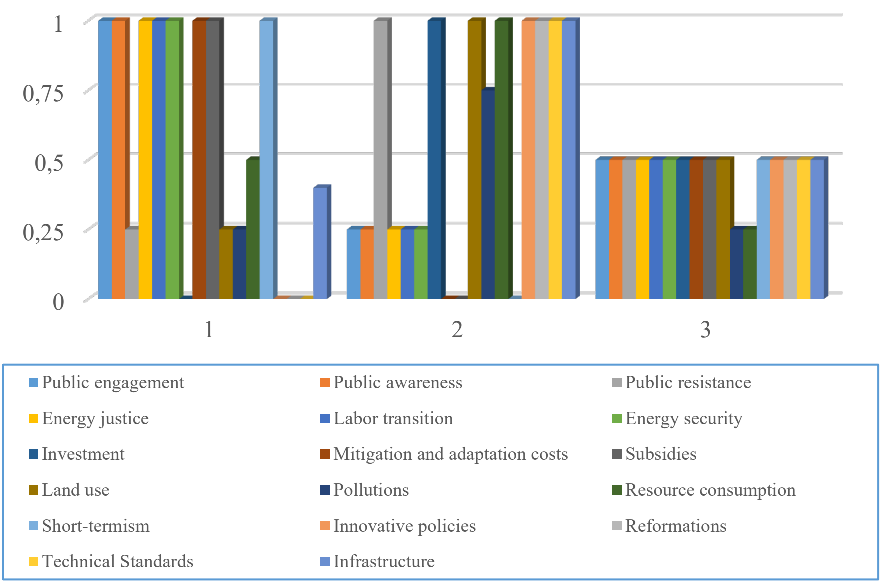

Figure 3.1 Initial values

Lithuania has encountered several challenges that have profoundly impacted its energy sector. These challenges and their related indicators have been systematically categorized in the study. The research emphasized the need for innovative policies and long-term strategic planning to surmount these hurdles. It also highlighted the significance of public awareness and acceptance. Also, the results indicated that these factors can substantially influence the success of low-carbon initiatives. The comprehensive analysis offered by the IFCM-TOPSIS approach contributes to understanding the complex interrelationships between different challenges.

The study results showed that the "Duet "scenario is the most effective strategy for Lithuania's low-carbon energy transition. This scenario outperformed others, highlighting the importance of integrating technological advancements and social considerations in policy-making. On top of that, the "People First" scenario was ranked second, prioritizing social needs and emphasizing the crucial role of public engagement. The study also highlighted that substantial financial resources are needed to move toward low-carbon technologies. By utilizing IFCM and TOPSIS, the study provided a comprehensive framework for evaluating and prioritizing different scenarios. The integrated methodological approach not only aids in identifying the most effective strategies and provides valuable insights for policymakers to address challenges.

A NOVEL TWO-STAGE MULTICRITERIA DECISION-MAKING APPROACH FOR SELECTING SOLAR FARM SITES: A CASE STUDY

This chapter presents the fourth article published in the *Journal of Cleaner Production*. The present article presents a novel method to find the most suitable places to build solar farms, and it is applied to Lithuania as a case study.

This chapter will investigate the sixth and seventh research statements: Land use is a severe challenge due to the extensive space requirements of renewable energy infrastructure and competition with other critical land uses; climate factors are crucial in determining the suitability of locations for building solar farms, but they are not the only considerations. The chapter can be considered as some part of the methodological part of the dissertation and its applications for finding suitable locations for building solar farms. This chapter is the primary practical part of the dissertation, and the proposed method can be practically used to solve academic and real-life problems.

The article aims to create and validate a comprehensive model for choosing the best solar farm sites in the Baltic region, focusing on Lithuania. It evaluates the technical suitability of potential sites based on a wide range of criteria, including environmental, economic, social, and technical factors. The model's application to a case study demonstrates its applicability. Figure 4.1. shows studied locations.

Figure 4.1. Potential locations

The selection of solar farm sites is crucial for optimizing the efficiency and sustainability of solar energy projects. Previous studies have emphasized the importance of considering various factors to ensure that solar farms are practical and sustainable. There is a need for models and methodologies to address the specific conditions and challenges of the Baltic region. The research seeks to answer the following key questions in order to advance the methodology of solar farm site selection:

- What are the critical factors that influence the selection of solar farm sites?
- How can an integrated model improve the decision-making process for selecting sites?
- How can the proposed model balance comprehensive evaluation and objective efficiency assessment?
- How can the model be effectively applied to a real-world case study in the Baltic region to validate its practical utility and relevance?
- What insights and guidelines can be drawn from the case study for future solar farm site selection in similar contexts?

The research utilizes a unique integrated methodology that combines DEA and the CRITIC-TOPSIS approach to improve the selection process for solar farm sites. DEA helps identify efficient and inefficient units by calculating efficiency scores. The study uses the DEA model to assess and compare potential solar farm sites by analyzing various factors.

In the second stage, the CRITIC method determines the criteria weights. Then, the TOPSIS method is applied to rank the solar farm sites. This integrated DEA-CRITIC-TOPSIS approach allows for a balanced, transparent, and robust decision-making process, improving resource allocation and ensuring the selection of the most suitable and sustainable solar farm sites.

The study examined factors such as temperature, solar irradiation, humidity, and wind speed to determine suitability. Also, the results indicated that the two-stage proposed method could accurately find the best locations for building solar farms.

The findings highlighted the importance of comprehensive evaluation of different criteria. Specific sites, such as those in Lithuania's Klaipėda and Šiauliai regions, showed a well-balanced combination of these factors. The successful identification of high-potential sites in Lithuania serves as a model for future renewable energy planning.

The study highlights the effectiveness of combining DEA and CRITIC-TOPSIS methods to evaluate potential solar farm sites. This combined approach accurately identified the best sites for solar farms in the Baltic region, specifically Lithuania. The main results indicated that Vilnius is the best location; however, sensitivity analyses showed that Klaipėda and Šiauliai ranked the best places to build solar farms in line with the global solar map. It could be concluded that factors like GDP could significantly impact selecting locations. The proposed method's ability to incorporate various criteria enables decision-makers to select technically viable and economically and socially sustainable sites. The proposed method supports sustainable energy development and contributes to regional economic growth.

CONCLUSIONS

The low-carbon energy transition faces various challenges, not only technical or economic. Also, since 2016, the number of publications in this context has increased due to the Paris Agreement. The findings suggest that governments should develop long-term strategies to mitigate climate change rather than pursue short-term benefits.

According to the second article, energy justice is the most significant social challenge. A just transition is the primary solution to this social challenge, as it prioritizes society in the energy transition.

In addition, the third research evaluated challenges as a dynamic system. In the Lithuanian energy system, "short-termism" is ranked as the second challenge. Although long-term strategies are crucial, short-term policies are essential for low-carbon economies. Short-term policies could improve public awareness and promote behavioral changes. Furthermore, according to the results of the third article, scenarios are a valuable tool for predicting the future of a system. FCM provides a detailed understanding of the future.

In the fourth article, DEA was integrated with CRITIC-TOPSIS to evaluate potential sites for solar farms. Climate suitability is the primary factor in selecting solar farm locations. Companies and decision-makers should first consider GDP and labor markets in places like Klaipeda if they want to build solar farms in Lithuania. After that, they can make decisions based on climate factors. Also, the proposed method can practically evaluate potential farms as the results align with other studies and the global solar map.

RESEARCH LIMITATIONS

- The missing data excluded Romania, Cyprus, Croatia, and Malta.
- Gathering expert opinions was time-consuming, as the experts were unfamiliar with the research method.
- Data processing was time-consuming and complicated.
- The lack of available data for some sites in the Baltic region was a limitation, leading to the removal of these sites from the analyses in the present research.

PRACTICAL IMPLICATIONS

Renewable Energy Support Mechanisms: Governments should establish mechanisms for renewable energy sources. For example, feed-in tariffs ensure that renewable energy producers receive stable returns. By guaranteeing stable returns on investment, these policies can significantly contribute to the transition to a low-carbon energy system.

Public Awareness and Education: Boosting public awareness and enhancing education about low-carbon energy are vital. It can be done through effective communication strategies, such as public information campaigns. Also, integrating sustainability into school curricula could improve public awareness. On top of that, individuals and communities should be empowered with beneficial knowledge toward a low-carbon energy system.

Technology and Innovation Investment: Investing in research and development enhances technological innovation, boosting the low-carbon transaction. Collaborating research institutes, governments, and the private sector could create a supportive innovation environment. This goal can be achieved through grants, subsidies, tax incentives, and public-private partnerships.

Comprehensive Scenario Planning: Scenario planning is beneficial in understanding potential future scenarios leading to a low-carbon energy economy. This approach evaluates and ranks scenarios based on various criteria, helping policymakers predict potential challenges and opportunities. Comprehensive scenario planning also assists in identifying effective pathways for achieving low-carbon goals. This holistic perspective addresses the uncertainties and risks of transitioning to a sustainable energy system.

Addressing Energy Justice and Security: It is vital to prioritize energy justice and security during the transition. Policies should address different aspects of energy justice. Energy security involves maintaining a reliable and resilient supply to meet demand without compromising social and environmental goals. This situation requires a diverse and flexible energy mix that includes renewable and conventional sources.

RECOMMENDATIONS FOR FUTURE RESEARCH

It is recommended that the socioeconomic impacts of the shift towards renewable energy, including its effects on employment, income distribution, and energy affordability, be examined. Strategies to ensure a just transition, such as training workers and implementing inclusive policies, should also be developed.

It is recommended that renewable energy projects have environmental and ecological effects, particularly their impact on ecosystems. Plans should be created to minimize negative impacts and improve sustainability.

It is recommended that future research concentrate on creating a geographical information system (GIS) framework for identifying the most suitable locations for solar farms.

It is recommended that future studies focus on the development of innovative grid technologies and advanced energy management systems. These systems, like the Internet of Things (IoT), are crucial for advancing renewable energy.

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SANTRAUKA

Energetikos sektoriuje išmetama daug šiltnamio efektą sukeliančių dujų (ŠESD), todėl perėjimas prie mažo anglies dioksido pėdsako energijos yra visuotinė būtinybė. Atsižvelgiant į išmetamų ŠESD poveikį visuotiniam atšilimui ir klimato kaitai, tai tapo viena svarbiausių pasaulinių problemų (Huang & Liu, 2021). Todėl buvo įgyvendinti įvairūs pasauliniai ir vietos susitarimai ir iniciatyvos, pavyzdžiui, Paryžiaus susitarimas ir Darnaus vystymosi darbotvarkė 2030, kuriuose daugiausia dėmesio skiriama mažo (arba nulinio) anglies dioksido pėdsako energijai (Sorman et al., 2020). Nepaisant tarptautinės paramos Paryžiaus susitarimui, energetikos politika vis dar turi užtikrinti sąžiningą ir veiksmingą anglies dioksido mažinimą visuose lygmenyse, atsižvelgiant į ekonominius, socialinius, aplinkosauginius, techninius, politinius ir institucinius iššūkius (Nuru et al., 2022). Be to, pertvarkos valdymas apima sudėtingą, daugialypį procesą, susidadantį iš daug veiksnių, lygių ir etapų. Jis palengvina sisteminį socialinių ir techninių sistemų perėjimą prie tvarumo (Markard & Rosenbloom, 2020). Šiam procesui reikalingos laipsniškos reformos, ypač autoritarinėse šalyse, kuriose nusistovėjęs „vadovavimo ir valdymo“ principas dažnai trukdo pereiti prie mažo anglies dioksido pėdsako energijos, dėl ko kyla konfliktų (Goldthau & Westphal, 2019). Sėkmingai mažo anglies dioksido pėdsako energijos pertvarkai būtinas platus inovatyvių technologijų ir reguliavimo pakeitimų pritaikymas, pavyzdžiui, standartų ir anglies dioksido kainų režimų nustatymas ar net reguliavimo panaikinimas, siekiant padidinti efektyvumą (Rosenbloom et al., 2018).

Vystant mažo anglies pėdsako energijos sistemas itin svarbu turėti scenarijų. Jis įtraukia technologinių inovacijų, ekonominių veiksnių ir reguliavimo pokyčių dinamiškos sąveikos supratimą (Van Vuuren et al., 2012). Sukuriant sistemą, kurioje būtų atsižvelgta į šias sudėtingas aplinkybes, suinteresuotieji subjektai, remdamiesi skirtingomis prielaidomis, gali parengti kelis scenarijus (Sovacool et al., 2019). Taip pat, siekiant sumažinti šiltnamio efektą sukeliančių dujų išmetamą kiekį, labai svarbu plėsti mažai arba anglies dioksido neišskiriančių energijos šaltinių, pavyzdžiui, saulės energijos, naudojimą (Kuşkaya et al., 2023). Nepaisant to, ribotos žemės galimybės – didelis iššūkis pereinant prie mažo anglies dioksido pėdsako energijos (Borras Jr & Franco, 2013). Dėl šios priežasties būtina nustatyti optimalias teritorijas statyti saulės jėgainių parkus (Wang et al., 2022). Ši idėja aprėpia įvairių veiksnių, darančių įtaką vietovių tinkamumui saulės jėgainių parkams įrengti, šių vietovių efektyvumo įvertinimą ir galiausiai tinkamiausios teritorijos saulės jėgainių parko plėtrai parinkimą (Stock & Birkenholtz, 2021).

Dėl šios priežasties, šiuo tyrimu siekiama sukurti išsamią sistemą, padedančią suprasti sudėtingus iššūkius, susijusius su perėjimu prie mažo anglies dioksido pėdsako energijos. Tyrime integruojami socialiniai, aplinkosauginiai, instituciniai ir ekonominiai elementai, siekiant susidaryti visapusišką vaizdą apie šios pertvarkos kliūtis ir strategijas joms įveikti. Tyrime daugiausia dėmesio skiriama plėtoti tikslinę politiką, skirtą spręsti tam tikrus iššūkius, ir pabrėžiami atskirų trukdžių nustatymas ir analizė, o ne pateikiama bendra apžvalga. Šiuo tyrimu siekiama sukurti išsamią sistemą, padedančią įveikti minėtus iššūkius naudojant daugiakriterinį sprendimų priėmimo (MCDM) metodą neapibrėžtose aplinkose. Yra įvertinama ES šalių veikla sprendžiant šiuos iššūkius, nustatant subjektyvų ir objektyvų nustatytų rodiklių svorį ir suskirstant šalis pagal jų veiksmingumą tvarkantis su minėtais iššūkiais.

Be to, tyrime naudojamas scenarijų kūrimas Lietuvos energetikos sistemos veiklai įvertinti, pasitelkiant tris skirtingus metodus. Pagal pirmąjį metodą, pirmenybė teikiama visuomenės gerovei, dėmesį kreipiant į rodiklius, glaudžiai susijusius su visuomenės interesais, tokiais kaip subsidijos ir visuomenės įtraukimo priemonės, o privačioms investicijoms skiriama mažiau dėmesio, kad būtų atsižvelgta į potencialų privačių įmonių nenorą prisidėti. Šiuo metodu tikimasi didesnių švelninimo ir pritaikymo išlaidų, susitelkiant į trumpalaikius sprendimus, mažai dėmesio skiriant novatoriškai politikai ir reformoms. Taip pat šiuo tyrimu siekiama sukurti išsamią sistemą įvertinti optimalios teritorijos pasirinkimą įrengti saulės jėgainių parkus Baltijos regione, sutelkiant dėmesį į Lietuvą. Norima įveikti ankstesnių tyrimų spragas, įvertinant platesnį veiksnių, turinčių įtaką teritorijos pasirinkimui, spektrą. Šie veiksniai aprėpia aplinkos veiksnius, pavyzdžiui, temperatūrą, vėjo greitį, drėgmę, kritulius, oro slėgį, saulėtumą, aukštį ir saulės energinę apšvietą.

Indėlis į ekonomiką

Perėjimas prie energijos, išskiriančios mažai anglies dioksido į aplinką, yra ekonomiškai intensyvus procesas, kuris keičia reguliavimą, įskaitant anglies dvideginio kainodarą ir standartus. Ekonominė valdymo modelių analizė sprendimus priimantiems asmenims gali padėti palyginti reguliavimo pakeitimų sąnaudas ir naudą.

Šiame tyrime pateikiamas ekonominis įrankis, pagal kurį šalys reitinguojamos pagal jų veiksmingumą sprendžiant šiuos iššūkius. Tai gali būti naudinga priimant būsimus investicinius sprendimus ir politikos reformas ES.

Šioje disertacijoje siūlomas vertinimo sistemas.

gali taikyti ekonomistai, kad įvertintų veiksnius, turinčius įtakos saulės energijos ūkio vietos parinkimui. Tai padeda geriau paskirstyti išteklius ir užtikrinti ilgalaikį ekonomikos tvarumą.

Tyrimo problema

Reikia integruotos iššūkių sistemos. Ši sistema turėtų nustatyti kliūtis ir problemas bei pagerinti šių iššūkių supratimą. Be to, reikalinga visapusiška vertinimo sistema, apimanti atitinkamus iššūkius. Tokia vertinimo sistema yra būtina, kad šalys galėtų tiksliai įvertinti savo veiklą sprendžiant šiuos iššūkius. Tai galėtų padėti sprendimus priimantiems asmenims parengti veiksmingas strategijas, kurios padėtų siekti ekologiškesnės ateities.

Be to, pradejus naudoti mažai anglies dioksido į aplinką išskiriančią energiją, reikalingos didelės pradinės investicijos, todėl labai svarbu susidaryti išsamų perėjimo planą. Sprendimus priimantys asmenys turi suprasti visus, perėjimo prie mažai anglies dioksido į aplinką išskiriančių technologijų ekonomikos aspektus, nes tai apsunkins tiek vyriausybes, tiek sociumą. Taip pat, ekonominiai veiksniai turėtų būti aptariami kartu su kitais veiksniais, pavyzdžiui, darbo rinka dinamiškoje aplinkoje, siekiant išsiaiškinti, kaip jų sąveika paveiktų ekonominę politiką apie anglies dioksido kainodarą ar subsidijas. Norint įveikti ekonominius iššūkius, reikia suderintų vyriausybių, privačių investuotojų ir tarptautinių institucijų veiksmų; todėl visų suinteresuotųjų šalių interesams atsižvelgti reikalinga visa apimanti sistema, kurią teoriškai ir praktiškai būtų galima panaudoti visuose etapuose.

Be to, reikia tinkamos scenarijų planavimo sistemos. Šalys turi modeliuoti skirtingus scenarijus, atsižvelgdamos į savo unikalius prioritetus ir išteklius, kad nustatytų realius tikslus. Tačiau esama literatūra nepateikia sistemos, apimančios visus iššūkius ir jų sąveiką. Be to, dabartinėje literatūroje reikia nuoseklių gairių, kaip įvertinti veiksnius, turinčius įtakos galimų vietų tinkamumui saulės energijos ūkiams statyti. Todėl norint palengvinti saulės energijos ūkio plėtrą, būtina sukurti išsamią svetainės tinkamumo analizės sistemą.

Tyrimo teiginiai

- Mažo anglies pėdsako energijos pertvarka nėra vien tik techninis perėjimas, nes tai yra ir socialiai techninė pertvarka, susidurianti su įvairias socialiniais, aplinkosauginiais, ekonominiais, instituciniais ir techniniais iššūkiais.
- Teisinga energijos pertvarka yra būtina mažo anglies pėdsako energijos pertvarkai, kadangi tai užtikrina, kad perėjimas prie švarios energijos šaltinių būtų tinkamas ir įtraukus.
- Dėl didelio poveikio aplinkai ir visuomenei, žemės naudojimas yra vienas svarbiausių iššūkių mažo anglies dioksido pėdsako energijos pertvarkoje.
- Būtina įtraukti visuomenę į mažo anglies dioksido pėdsako energijos ateities scenarijų kūrimą. Toks metodas skatina visapusiškesnį, veiksmingesnį ir tvaresnį pertvarkos procesą.
- Žemės panaudojimas – didžiausias iššūkis mažo anglies dioksido pėdsako energijos pertvarkai, nes atsinaujinančios energijos infrastruktūrai keliama daug reikalavimų ir yra konkuruojama su kitais svarbiais žemės panaudojimo būdais.
- Klimato veiksniai svarbūs nustatant vietovių tinkamumą saulės jėgainių parkams statyti, bet jie nėra vieninteliai veiksniai, darantys įtaką šiam sprendimui. Įvairūs aplinkosauginiai, ekonominiai, socialiniai ir reguliuojantys veiksniai taip pat privalo būti apsvarstyti.

Disertacijos struktūra

1 skyrius. Šiame skyriuje pristatomas pirmasis su disertacija susijęs straipsnis, kuriame pateikiama sistematiška literatūros apžvalga, skirta nustatyti mažo anglies dioksido pėdsako energijos pertvarkos iššūkius. Pristatomas pirmasis „Energy Strategy Reviews“ žurnale publikuotas straipsnis, pavadinimu „Challenges to the low carbon energy transition: A systematic literature review and research agenda“ (*liet.* „Mažo anglies dioksido pėdsako energijos pertvarkos iššūkiai: sistematiška literatūros apžvalga ir mokslinių tyrimų planas“). Šiame straipsnyje pateikiami nustatyti mažo anglies dioksido pėdsako energijos iššūkiai, tapę su šia disertacija susijusių straipsnių pagrindu. Be to, apžvelgti tos pačios temos literatūroje pateikti taikomieji tyrimų metodai ir pasiūlytas išsamus mokslinių tyrimų planas.

2 skyrius. Šiame skyriuje pristatomas antras su disertacija susijęs straipsnis, kuriame naudojamas naujas daugiakriterinių sprendimų priėmimo metodas įvertinti ES šalių veiklą, sprendžiant pirmajame skyriuje nustatytus iššūkius. Pristatomas antrasis "Sustainable Environment Research "žurnale publikuotas straipsnis, pavadinimu "A novel multicriteria assessment framework for evaluating the performance of the EU in dealing with challenges of the low-carbon transition: an integrated Fermatean fuzzy approach "(*liet.* "Nauja daugiakriterinė vertinimo sistema įvertinti ES veiklą, sprendžiant mažo anglies dioksido pėdsako energijos pertvarkos iššūkius: neapibrėžtas Fermato metodas "). Straipsnyje tiriama ES šalių veikla, sprendžiant 1 skyriuje nustatytus iššūkius, naudojant MCDM metodą.

3 skyrius. Šiame skyriuje pristatomas trečias su disertacija susijęs straipsnis, kuriame naudojami kognityviniai žemėlapiai iliustruoti nustatytų iššūkių ryšius ir Lietuvos energetikos sistemai sukurtus scenarijus. Pristatomas trečiasis "Journal of Innovation & Knowledge "žurnale publikuotas straipsnis pavadinimu "An analysis of challenges to the low-carbon energy transition toward sustainable energy development using an IFCM-TOPSIS approach: A case study "(*liet.* "Mažo anglies dioksido pėdsako energijos perėjimo prie tvarios energijos plėtros iššūkių analizė taikant IFCM-TOPSIS metodą: atvejo analizė "). Straipsnyje analizuojami keli perėjimo prie mažo anglies dioksido pėdsako energijos sistemos Lietuvoje scenarijai, naudojant kognityvinius žemėlapius, sukurtus pagal 1 skyriuje nustatytus iššūkius ir 2 skyriuje nustatytus rodiklius.

4 skyrius. Šiame skyriuje pristatomas ketvirtas su disertacija susijęs straipsnis, kuriame naudojamas naujas dviejų etapų metodas įvertinti potencialių vietovių saulės jėgainių parkams Lietuvoje statyti veiksmingumą, o vėliau reitinguojamos potencialios ir efektyvios vietos. Pristatomas ketvirtasis „Journal of Cleaner Production“ žurnale publikuotas straipsnis, pavadinimu „A novel two-stage multicriteria decision-making approach for selecting solar farm sites: A case study“ (*liet.* „Naujas dviejų etapų daugiakriterinių sprendimų priėmimo metodas saulės jėgainių parkų vietovių pasirinkimui: atvejo analizė“). Straipsnyje pristatomas naujas metodas vietovėms, tinkamiausioms statyti saulės jėgainių parkus, nustatyti. Šis metodas yra naudojamas Lietuvos atvejo analizei.

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PRESENTATION AND CONFERENCE PROCEEDINGS

- Saraji, M. K. (2021, December 2). A framework for evaluating the challenges to sustainable smart city development. 16th Prof. Vladas Gronskas International Scientific Conference, Kaunas, Lithuania.
- Saraji, M. K. (2021, September 17-20). Multicriteria assessment of low carbon energy transition. IV International Science Conference SER 2021, Igalo (Herceg Novi), Montenegro.
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- Saraji, M. K. (2023, December 1-3). Low-carbon energy transition: A review. 5th International Conference on Social Sciences, Humanities and Arts (ICSHA), Paris, France.

INTERNSHIPS AND STUDY VISITS

Mahyar Kamali Saraji did six months of internships from 2023/12/01 to 2024/05/31 at Politechnika Wrocławskam, Poland, under the supervision of Prof. Vishnu Suresh. The primary purpose of the visit was to apply Python to the energy sector. The internship helped the PhD candidate write and analyze the last chapter of the dissertation.

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Challenges to the low carbon energy transition: A systematic literature review and research agenda

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ABSTRACT

Many challenges should be tackled in transitioning to a low-carbon energy system, motivating many researchers to study these challenges. In this context, the present study aims to identify challenges through a systematic literature review of studies published between 2006 and 2023 to propose a comprehensive framework of challenges. To this end, the PICOC framework was applied to set the research scope properly; and an integrated method called PSALSAR protocol was used to find, evaluate, and review publications published in Scopus and the Web of Science. As a result, 123 articles were reviewed, and seventeen challenges were identified and classified into five social, economic, environmental, technical, and institutional challenges. Results indicated that international agreements on climate change could boost the number of studies on the low-carbon energy transition. Also, it is indicated that researchers applied qualitative methods more in earlier studies, and methods and topics have become more profound over the years.

1. Introduction

The energy sector is the leading contributor to greenhouse gas (GHG) emissions, making the low-carbon energy transition a global trend [1] since GHG emissions affect global warming and climate change, the most important issues globally. Transition to a low-carbon energy system is a reaction to the dual challenges of sustainable development and climate change, requiring rapid and radical socio-technical changes [2–4]. For instance, according to the Paris agreement, a global 60%–80% reduction in GHG emissions by 2050 needs the broad adoption of low-carbon products and services, including hybrid, hydrogen fuel cells, low-energy automobiles, and residential solar panels. Furthermore, several agreements and agendas on global and local scales have been adopted, including the Paris agreement and the 2030 agenda for sustainable development, in which low (zero)-carbon energy is the primary goal [5–7]. Therefore, many countries look for renewable and sustainable alternatives to current energy systems owing to the growing energy demand, CO2 reduction, the dwindling reserves of fossil fuels, and climate change [8,9].

Also, the Fifth Assessment Report (AR5) of the United Nations' Intergovernmental Panel on Climate Change (IPCC) emphasizes the need for nations to find alternatives to fossil fuels. The IPCC advises that by 2050, at least 80% of the world's energy supply should be renewable to avert some of climate change's most catastrophic impacts [10]. However, despite the international confidence expressed in the Paris agreement, energy policies have failed to deliver equitable and effective carbon reductions at all levels since several challenges stemming from economic, social, environmental, technical, political, and institutional challenges. Therefore, to overcome these challenges and to keep global warming far below 2°, international, national, and local authorities, researchers, and communities must work on all fronts [11,12]. To this end, many researchers have studied challenges to low carbon energy transition over the years as academics worldwide play a critical role in facilitating the energy transition [13,14].

For instance [15], have studied the energy transition in Canada and concluded that public education is one of the crucial factors affecting the energy transition; it boosts public awareness and engagement. Also, Baran et al. (2020) have investigated the low-carbon energy transition from a labor market perspective in coal-based countries, and they concluded that even if all new jobs in green industries would be filled by workers who used to work in coal-based sectors, there is still a gap in the job market. Stavrakas [10] have also investigated the barriers to low-carbon energy transition in Greece and the consequences of adopting renewables. They concluded that Gross Domestic Product (GDP) and labor productivity would temporarily decrease during the energy transition; however, investments in Renewable Energies (REs)

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could affect the duration and intensity of the transition's effects. Also, Nochta and Skelcher (2020) conducted a comparative analysis across the EU to investigate the role of the states in the low-carbon energy transition; they concluded that budget constraints could affect the public sector's capacity to boost climate change adaptation and mitigation.

Moreover [16], has investigated environmental justice and conflicts in wind energy as environmental challenges of the low-carbon energy transition. The results indicated that land acquisition is one of the distinguished aspects of the global land rush, changing land-use patterns. Also, Seck et al. (2020) investigated the interactions between supply limitations and low-carbon energy transition. They concluded that demand-control measures should accompany the massive growth in copper consumption, and copper recycling industries should not jeopardize energy production. Also, Goldthau and Westphal (2019) have investigated short-termism in petrostates as an institutional challenge. They concluded that petrostates prefer short-term income even if it affects their long-term income from oil production since short-termism is crucial for their political positions. Also, Kuamoah (2020) has investigated REs adoption in Ghana under the Sustainable development Goals (SDGs). The results indicated that one of the barriers to low-carbon energy transition is the lack of infrastructure, considered a technical challenge, especially unstructured energy grids.

As there are many challenges to the low-carbon energy transition, it would be challenging to follow climate change agreements and agendas at the necessary pace. On top of that, The low-carbon energy transition is a socio-technical transition that simultaneously requires dealing with many challenges, barriers, and issues [17]. Therefore, there is a need for a comprehensive framework in which challenges to the low-carbon energy transition are presented in detail to assist decision-makers in dealing with challenges by improving the required knowledge around challenges and solutions founded by researchers over the years. Furthermore, researchers need to know the current status quo of the challenges to the low-carbon energy transition to move forward. Therefore, the present study aims to conduct a systematic literature review to assist academics and authorities in dealing with the low-carbon energy transition. To this end, the Protocol, Search, Appraisal, Synthesis, Analysis, and Report (PSALSAR) framework is applied to review the literature from 2006 to 2023. Subsequently, the framework of Population, Intervention, Comparison, Outcome, and Context (PICOC) is employed to set the research scope. The main contributions of the present study are presented in the following.

- To propose a comprehensive framework of challenges to the low-carbon energy transition. A comprehensive framework helps identify and address the barriers and obstacles hindering the low-carbon energy transition. By understanding and tackling these challenges, policymakers and stakeholders can devise effective strategies to accelerate the transition. Also, By understanding the specific challenges, researchers and technology developers can focus on developing solutions that directly address the critical issues faced during the transition.
- To review applied methods for dealing with the low-carbon energy transition challenges. By reviewing the methods and strategies that have been previously applied, policymakers and stakeholders can learn from both successful and unsuccessful experiences. Also, The energy transition is a complex and evolving process. Regularly reviewing the methods helps in identifying areas that require improvement and adjustment. This iterative process enables the implementation of more effective solutions over time, ensuring the transition stays on track and adapts to changing circumstances.
- To illustrate the distributions of studies considering publication year and journals. By plotting the distribution of studies based on publication year, researchers and policymakers can identify trends in the number of publications over time. It helps in understanding the growth of interest in the low-carbon energy transition, the rate of research output, and whether there are any significant spikes or lulls in research activity. Also, Journals' reputations and impact factors can indicate the influence and visibility of the research published in them. Analyzing the distribution of studies across journals can help researchers understand the reach and impact of their work and others in the field.
- To provide a research agenda according to the future research directions given by researchers. A research agenda aligned with their identified future research directions helps prioritize addressing these critical gaps, ensuring that research efforts are focused on areas of maximum impact. Also, incorporating researchers' insights makes the research agenda more relevant and practical. It ensures that the research questions and objectives align with real-world challenges and needs, increasing the likelihood of producing actionable findings and applicable solutions.
- To provide policy recommendations based on reviewed articles. Policy recommendations grounded in reviewed articles provide policymakers with evidence and data-driven insights. It helps ensure that policy decisions are based on reliable information and research findings rather than opinions or assumptions. The policy recommendation is crucial in ensuring that policy decisions are well-informed, evidence-based, and aligned with international goals. By drawing on the knowledge in peer-reviewed literature, policymakers can design effective, efficient, and sustainable policies to accelerate the transition to a low-carbon energy future.

The remainder of the present study is as follows: section 2 presents the integrated research method for identifying, refining, and selecting publications within databases. Section 3 investigates the distribution of the papers through tables and charts. A comprehensive model is proposed and discussed in section 4. Section 5 provides conclusions, future directions, and research limitations.

2. Research method

The SALSA, search, appraisal, synthesis, and analysis, a framework is used to search and analyze the literature. The technique enables a thorough literature review while minimizing the possibility of subjectivity [18–20]. The SALSA technique is recognized in the scientific literature as an effective instrument for finding, analyzing, and systematizing scientific and practical investigations. It also ensures the work's methodological accuracy and completeness [20]. Additionally, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement assures the uniformity and thoroughness of research [21]. The PRISMA statement comprises a 27-item checklist and a four-phase flow diagram, including identification, screening, eligibility, and included papers [22–25]. However [26], proposed a new approach by integrating PRISMA and SALSA, abbreviated as PSALSAR, which has six main steps: Protocol, Search, Appraisal, Synthesis, Analysis, and Report. The present study employs an

Table 1
Methodology for systematic literature review.

Steps	Tasks	Approaches
Research protocol	Study scope: identifying the challenges to the low-carbon energy transition	The PICOC
Searching	Searching for publications related to the research goals	Searching in Scopus and Web of Science (WOS) using specific keywords
Appraisal	Selecting eligible studies	The PRISMA protocol
Synthesis	Classification information extracted from included articles	The PRISMA: a 27-item checklist
Analysis	Analyzing the classified information and proposing a novel framework of challenges	The PRISMA: a 27-item checklist
Report	Summarizing the results of analyses in the form of an article	The PRISMA: a 27-item checklist

integrated PSALSAR technique. Table 1 presents the methodology for conducting a systematic literature search to identify low-carbon energy transition challenges.

Step 1. **Research protocol**. It contributes to the literature evaluation's transparency, reproducibility, and systematic character and reduces subjectivity in the study undertaken. The critical objective at this stage is to specify the scope of the present research. Research questions may be developed, and the most relevant strategies for accomplishing the study aim can be chosen. The PICOC framework is an effective tool for defining the scope of research, which was employed in this study. The framework establishes a rigid structure that enables an examination of the research questions in terms of their constituent ideas, defining the study's purpose [20,27]. Table 2 summarizes the PICOC framework used in the present study.

The main research questions are presented in the following.

1. What impediments and obstacles are encountered in implementing the low-carbon energy transition?
2. What methodologies are employed to address the challenges to the low-carbon energy transition?"
3. What are the main research gaps in the low-carbon energy transition context?

Step 2. **Searching**. It entails developing and implementing a search strategy. It is critical to select the appropriate database to ensure that the literature obtained is of good quality and represents the majority of papers accessible. To this end, all articles indexed on Scopus and Web of Science have been found by the following research strings:

Scopus: TITLE-ABS-KEY (("low carbon energy transition") OR ("low carbon transition") OR ("green energy transition") OR ("just energy transition") OR ("renewables" AND "energy transition")) OR ("challenge" AND "renewable" AND "energy transition"))

WOS: All=((low carbon energy transition) OR (low carbon transition) OR (just energy transition) OR (green energy transition) OR (renewables AND energy transition) OR (renewables AND energy transition) OR (challenge AND renewable AND energy transition))

Step 3. Appraisal. The selected articles have been evaluated considering the present research aims; thus, only publications meeting the search requirements are selected using the PRISMA protocol. The following requirements apply to inclusion: firstly, search keywords should be in the title, abstract, or keywords, and secondly, articles should be published in a scientific peer-reviewed journal. Also, the following requirements apply to exclusion: editorial letters, chapter books, review papers, academic theses, conference proceedings, duplicated publications, and non-English language studies. Fig. 1 indicates the research information flow.

Step 4. **Synthesis**. The extracted information has been classified into general and specific categories. The publication year, journals, case study location, and future directions were general information, while research gaps, aims, results and methodologies addressed challenges, and their type was specific information that addressed the research questions. The identified challenges were classified into social, economic, environmental, technical, and institutional.

Step 5. **Analysis**. This stage seeks answers to the core research questions and analyzes the categorized data concerning the research requirements. The results of this stage are presented in section three.

Step 6. **Report**. This step entails the presentation of critical points stemming from step 5. The PRISMA statement's 27-item checklist presents the literature review outcomes.

Table 2
The PICOC framework for justifying the research scope.

Concept	Definition	Application
Population	Studies on challenges to the low-carbon energy transition	Articles in which a novel methodology, conceptual framework, etc., were applied to cope with at least one of the challenges to the low-carbon energy transition
Intervention	The status quo of challenges to the low-carbon energy transition in the world	Giving a complete picture of the challenges to the low carbon energy transition and methodologies to deal with them
Comparison	Highlighting a specific challenge, not a broad picture	Developing policies to deal with a particular challenge to the low-carbon energy transition
Outcome	Challenges and sub-challenges to the low-carbon energy transition	A comprehensive framework of challenges to the low carbon energy transition, which includes all social, environmental, institutional, and environmental aspects
Context	Finding the various features included in the low carbon energy transition studies	Challenges, methodologies, future directions, gaps, and aims of studies

3. The status quo of the low-carbon energy transition

Many journals and publishers have contributed to extending the low-carbon energy transition. According to the results, "Energy Research & Social Science" has contributed the most to the literature with 15 published articles, followed by "Energy Policy" with 12 published articles. The distribution of the journals based on the published article is shown in Fig. 2.

Moreover, the distribution of articles based on the publication year shows a growing interest in studying the low-carbon energy transition after 2016; 24 articles were published in 2020, and most were published yearly. Fig. 3 illustrates the distribution of papers based on publication year.

2.1. Publications between 2006 and 2015

All articles published over a decade before the Paris agreement are discussed in Table 3. The number of published articles addressing challenges was not high before the Paris agreement. The studies published over this period tried to find the relationship of the energy

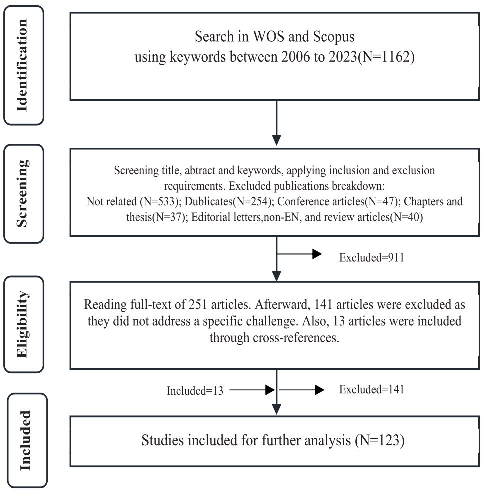

Fig. 1. Research information flow.

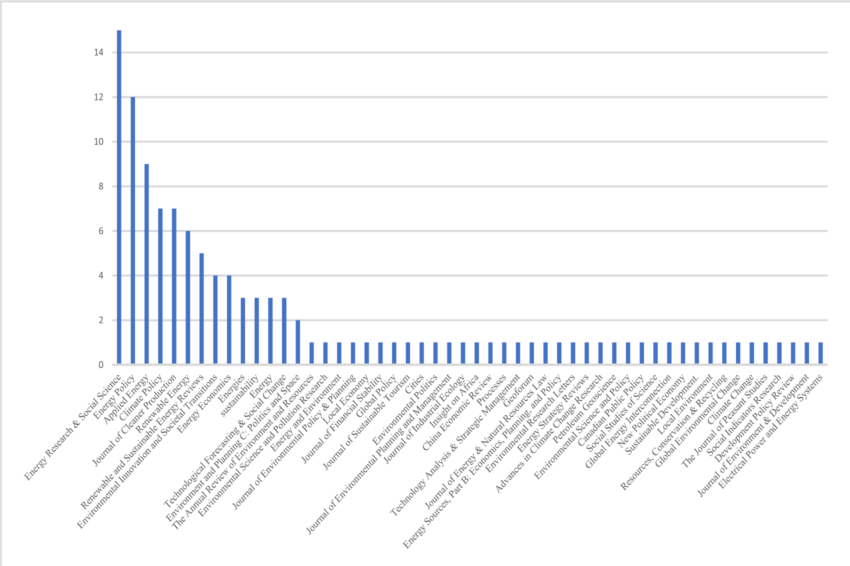

Fig. 2. Distribution of journals based on published papers.

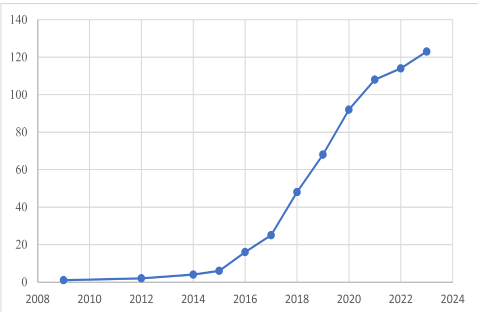

Fig. 3. Distribution of papers based on publication year (cumulative).

transition with other concepts in the energy sector, such as energy security.

2.2. *Studies published in 2016*

The Paris agreement was ratified in 2016, impacting the number of studies in this field. Most of the studies employed qualitative methods as they are more useful when there is no solid background on a specific topic. Table 4 discusses the published articles in 2016.

2.3. *Studies published in 2017*

Studies in 2017 also employed more qualitative methods; however, the footprint of quantitative and comparative methods could be seen in this period. Also, European countries conducted more studies this year. Table 5 presents the published articles in 2017.

2.4. *Studies published in 2018*

Many quantitative methods, such as the agent-based model, Monte Carlo, regression analyses, and fuzzy methods, were employed in 2018. However, some studies also applied qualitative methods, such as content analysis. Table 6 presents the published articles in 2018.

2.5. *Studies published in 2019*

More complex methods were applied in 2019 to deal with various research gaps related to the low-carbon energy transition; however, researchers applied more quantitative methods than qualitative ones. Table 7 presents the published articles in 2019.

2.6. *Studies published in 2020*

Many valid and complicated mathematical methods, such as the multi-level perspective (MLP) or Computable general equilibrium, were proposed and applied by starting a new decade. Also, Chinese researchers contributed more compared to before. The highest number of articles related to this field was published this year., Table 8 presents the published articles in 2020.

2.7. *Studies published in 2021*

Comparative and content analyses were applied more in 2021, primarily by Chinese researchers. Also, researchers studied more on just energy transition, trying to focus more on the social consequences of the low-carbon energy transition. Table 9 presents the published articles in 2021.

2.8. *Recent studies published in 2022-23*

The footprint of Covid-19 could be seen in recent studies, and quantitative approaches were applied more, primarily by researchers from China. The applied methods and topics are more profound than the earlier studies. Table 10 presents published articles in recent years, 2022–2023.

Table 3
Publications between 2006 and 2015.

Author (s)	Methods	Research gap	Study aims	Case study location
[28]	PowerPlan model, Long-range Energy Alternatives Planning model (LEAP), and Regional Energy Model (REM)	Need to implement low-carbon energy technologies in China and India as they are dependent on fossil fuels	the implications of low-carbon energy transitions in China and India	China and India
[29]	Social network analysis (SNA)	Need to change customer behavior to approach low carbon energy transition	To study the effect of social influencers on customer behavior related to the low-carbon energy transition	–
[30]	Autoregressive moving average (ARMA)	Need to understand whether a low-carbon-energy transition could be sustained after the Fukushima accident.	To analyze various exogenous shocks' impacts on electricity consumption	Japan
[31]	Qualitative Comparative Analysis	Need to investigate the low-carbon energy transition challenges	To investigate the relationship between energy security, technology scale, and decarbonization in the UK	UK
[32]	Qualitative Comparative Analysis, interviews	Need to understand the governance strategies for transition	To investigate the uncover governance challenges associated with the low-carbon energy transition	UK
[33]	Linear programming	Lack of studies that assess emerging countries' progress toward low-carbon energy transition	To evaluate the decarbonization strategies in Nicaragua for 2014–2030	Nicaragua

3. Challenges to the low-carbon energy transition

The present study classified challenges into five classifications and proposed a framework of challenges to the low-carbon energy transition. The five pillars of the proposed framework are explained below. Afterward, each identified challenge is explained in detail.

- Social pillar: challenges classified in this pillar directly affect people or are affected by them. For instance, public acceptance is a critical challenge to the low-carbon energy transition, which is closely connected to public engagement; therefore, stakeholders, including governments, should boost public acceptance by increasing public engagement. Also, public awareness affects any social transition, including low-carbon energy transition. There is an interconnection between public awareness and education, meaning improving public education could boost awareness. However, resistance to change is another barrier to any social transition due to the lack of awareness and engagement, which causes changes in consumer behavior. Also, the low-carbon energy transition might affect the revenue of those

Table 4
Studies published in 2016.

Author (s)	Methods	Research gap	Study aims	Case study location
[34]	Qualitative Comparative Analysis	The Transition Policies to sustainable energy have the potential for democracy; however, there is not enough debate.	To bring low carbon energy transition theory into conversation with relational and constructivist Science and Technology Studies on public participation	UK
[35]	Qualitative Comparative Analysis	Need to investigate the civic ownership structures and interplay of financial institutions.	To compare the emerging civic energy sectors in two countries to find the enabling role of financial institutions	UK, Germany
[36]	Qualitative Comparative Analysis	Need to investigate the relationship between low-carbon energy transition and the global geography of power.	To bridge three insights, including socio-technical transitions, energy geographies, and the rising powers as (re) emerging development donors	Mozambique and South Africa
[37]	Qualitative Comparative Analysis, Interviews	Need to investigate the relationship between low-carbon energy transition and political structure.	To study the impact of neo-liberalization and low-carbon energy transition	Kenya
[38]	Scenario planning	Need to investigate the low-carbon energy transition challenges.	To examine the low-carbon energy transition development through various scenarios in China	China
[39]	Qualitative Comparative Analysis	Need to analyze the effect of structural factors affecting low carbon energy transition.	To investigate the low carbon energy transition policies in two countries labeled as two opposite forms of capitalism	Germany and UK
[40]	Qualitative Comparative Analysis	Need to study where urban low-carbon energy transitions are governed.	To investigate how various governance processes are integrated to boost urban low-carbon energy transitions.	Norway
[41]	Mathematical model and scenario planning	Need to investigate the investment risk in low-carbon technologies.	To study the perceived risks' impacts on electricity prices from semi-dispatchable concentrated solar power	Algeria, Egypt, Morocco, and Tunisia

(*continued on next page*)

Table 4 (*continued*)

Author (s)	Methods	Research gap	Study aims	Case study location
[42]	Qualitative Comparative Analysis	Need to investigate the potential conflicts between low-carbon energy transition and long-term environmental policies.	To identify practical government arguments in Sweden which could reduce the conflicts between low carbon transitions and long environmental policies concerning EQOs	Sweden
[2]	Qualitative Comparative Analysis and literature review	The lack of studies on the role of institutions in the low-carbon energy transition.	To show the advantages of applying a more comprehensive set of institutional theories to the low-carbon energy transition' studies	China, Germany, and the UK

stakeholders who profit from the current system. Moreover, job loss and creativity are two essential side-effects of each social transition, including the low-carbon energy transition. The created jobs in green industries should adequately fill the gap caused by the low-carbon energy transition in the labor market; otherwise, the transition might face serious resistance due to the high numbers of high job loss, especially in highly dependent industries to fossil fuels. Furthermore, the low-carbon energy transition should guarantee secure and affordable energy. Energy poverty is one of the global challenges in the energy sector which should be addressed. A just energy transition is a crucial solution to energy poverty, motivating the present study to include energy justice in the proposed framework.

- Economic pillar: it comprises challenges to the low-carbon energy transition affecting investment in the energy sector, creating competitive advantages, and stimulating economic growth. For instance, all stakeholders should consider investment risk in any socio-technical transition, including low-carbon energy transition. The low-carbon transition might temporarily decrease labor productivity and GDP, but these effects' time duration and intensity depend on the investment amount. Low-carbon transition requires a considerable investment since it requires severe shifts in current technologies, standards, and customer behavior. As a result, governments should provide incentives, such as subsidies, for investors to increase their contributions. Although energy subsidies might boost low-carbon energy development, they might be a barrier to the low-carbon energy transition since governments still give considerable subsidies on fossil fuels to secure energy accessibility. Furthermore, energy transition costs should be addressed as severe challenges to the low-carbon energy transition, including adaptation and mitigation costs. Mitigation costs refer to spending for reducing GHG emissions, and Adaptation costs refer to spending for building a more resilient society to climate change.
- Environmental pillar: it comprises challenges affecting climate change, environmental pollution, natural resources consumption, and land use. A severe challenge to the low-carbon energy transition is resource consumption, such as sand consumption for building green and energy-efficient buildings or lithium, selenium, gallium, cadmium, tellurium, and germanium used in energy storage and solar photovoltaic panels. On the other hand, landfills for waste management and land use on a massive scale for building solar and wind farms are critical challenges to the low-carbon energy transition. For instance, green grabbing is a new form of land acquisition in which land and natural resources are dispossessed under sustainable development goals. Also, recycling lithium-ion batteries would not be a pollution-free activity; pyrometallurgy is a high-energy process that generates GHG emissions and poisonous fumes, and its hazardous waste must be landfilled.

Table 5
Studies published in 2017.

Author (s)	Methods	Research gap	Study aims	Case study location
[43]	Regression analyses	Lack of study on phase-out policies for the low-carbon energy transition.	To investigate Germany's nuclear phase-out policy's effect on renewable power generation technologies.	Germany
[44]	Qualitative Comparative Analysis	Need to elaborate on the energy constitution concept.	To study the energy constitution in the UK and how it affects low-carbon energy transition.	UK
[45]	Survey	Need to deal with the high cost of investment in transition.	To propose a new theory to replace the neoclassical notions of investment and capital market	UK
[46]	Comparative analyses	Need to Democratize energy system transitions.	To propose an accurate picture of the impacts of (in)justice on low carbon energy transition	–
[47]	Qualitative Comparative Analysis	Need sustainable pathways toward low-carbon energy transition.	To analyze three groups of low-carbon transition methods	–
[48]	Qualitative Comparative Analysis	Need to develop strategies for having fossil-free energy systems.	Study how Nordic countries want fossil-free energy systems by 2050 and the challenges.	Nordic countries
[49]	Survey	Need to develop new supportive policies.	To propose approaches for developing comprehensive policies	–
[50]	Survey and interview	To bridge the gap between techno-economic and societal disciplines and theory and practice in energy futures research.	To study which type of decarbonizing is preferable: centralized or decentralized	Germany
[51]	linear programming	Need to study how solar photovoltaic (PV) could boost energy access in an eco-friendly and affordable manner.	to investigate strategic directions and their impact on global energy sustainability through solar PV	India, Nigeria, Congo, Bangladesh, Ethiopia

Table 6
Studies published in 2018.

Author (s)	Methods	Research gap	Study aims	Case study location
[52]	Qualitative Comparative Analysis	Need to study causal inferences and community Perspectives concerning perceived energy (in) justice.	To analyze low carbon energy transition considering the justice concept	Denmark, Germany
[53]	Content analysis	To study the gap between energy transition and energy security	To propose a decision support system concerning energy security and energy transition	South Africa
[54]	Theoretical approach	Need to study the effect of policies on low-carbon energy transitions	To study alternative pathways for disruptive risks stemming from policies' risk concerning variable renewable electricity (VRE)	Finland
[55]	Comparative analyses	Need governmental support in the low-carbon energy transition	To investigate how governmental support could affect energy transition	China
[56]	the survey and interview	Need to study the roles of citizens and public engagement in the low-carbon energy transition.	To link energy citizenship to developments in Science and Technology Studies (STS)	Denmark
[57]	Interviews	The tourism sector should reduce its CO_2 emission	To figure out the tourism sector's understanding of the decarbonization challenge	–
[58]	Descriptive statistic	Need to consider energy justice in transition	To introduce energy justice considering the federal policies in India	India
[59]	Statistical Method	Need to study Nordic countries' experiences in the low-carbon energy transition to get lessons.	To investigate low carbon energy transitions in the Nordic countries for four decades, considering the Environmental Kuznets Curve (EKC)	Nordic countries
[60]	Mathematical model and scenario planning	Need to study the various technologies applied in the decarbonized energy system	To evaluate the applicability of marine energy compared to other technologies in the UK	UK
[61]	The employment factor approach, CGE models	Need to study the effect of the energy transition on the labor market	To study net employment impacts from energy transition in the EU	EU
[62]	fuzzy cognitive map (FCM), dynamic stochastic general equilibrium (DSGE) model, Business Strategy Assessment Model (BSAM)	Need to study the possible uncertainties in transitions	to study the barriers to low carbon transitions in Greece	Greece
[63]	Qualitative study: individual and group interview	Need to develop new political paradigms for the low-carbon energy transition.	To investigate how renewable industries should be promoted in China concerning the up-down approach.	China
[64]	Qualitative Comparative Analysis, Interviews	Need to analyze low carbon transition based on a justice perspective	To study how finance shapes the justice energy transitions outcomes and how energy policy shapes these justice outcomes	UK-Germany
[65]	Linear regression model	Need to know policy credibility is formed	To investigate whether understanding of policies' credibility depends on the current policy mix	Germany
[66]	Theoretical approach	Need to study the local and governmental support in the transition	To propose a framework of contributions to the low-carbon transition	Cologne
[67]	"Price-gap" approach	Need to remove the subsidies to move toward low carbon energy transition	To study the effect of removing fossil fules' subsidies on energy transition	China
[68]	Agent-based model and Monte Carlo	Need to evaluate the investment risk	To develop a model for assessing the impacts of investment on the development of an energy system	China
[15]	Qualitative Comparative Analysis	Need to investigate how low carbon energy transition will unfold in Canada	To examine the features of transition experiments	Canada
[69]	Linear programming	Need to transform from current coal-fueled systems to low-carbon energy systems.	To propose a transition plan to shut down the current system and integrate REs into the grid.	–
[70]	MESSAGE, Scenario planning	Need to study the current uncertainty in the future costs of large-scale variable renewable energy (VRE)	To investigate future storage implications and costs of hydrogen technology for low-carbon energy transitions	–
[71]	Linear programming	Need to study transmission investment as a critical element in the low-carbon energy transition.	To propose a hub based on transmission investment strategy for countries in a region	Romania-Turkey

Table 7
Studies published in 2019.

Author (s)	Methods	Research gap	Study aims	Case study location
[72]	Hypothetical Extraction Method (HEM)	Need to study the effect of the energy transition on the labor market	To apply a hypothetical model to address the neglected impacts of the energy transition on the labor market	UK
[73]	Semi-Structured Interview	Need to investigate energy justice in transition	To study the level of injustice in four European energy transition	Germany, France, the UK, and Norway
[74]	Mathematical model	Need to study the investment uncertainty	To propose a model to deal with investment uncertainty	China
[75]	"Price-gap" approach	Need to remove the subsidies to move toward low carbon energy transition	To study the effect of the metallurgical industry's subsidies on energy transition	China
[76]	NET-Power model	Need to evaluate the pathways of energy transition	To develop six scenarios for energy transition considering the transition cost	China
[77]	The survey, Qualitative Comparative Analysis	Need to transform common lands into solar parks	Investigate the economic and political procedure of transforming common lands belonging to agropastoralists into solar lands.	India
[78]	Real Options Analysis	Need to identify the challenges to the low-carbon energy transition	to conduct a quantitative analysis of investment barriers to the energy transition	Russia
[79]	Semi-Structured Interview	Need to investigate energy justice in transition	To study injustice types in four European energy transition	Germany, France, the UK, and Norway
[80]	TIMES Framework, scenario planning	Need to evaluate the various pathways to achieve a low-carbon energy system	to study the role of bioenergy in the low-carbon energy transition	Canada
[81]	MCDA	Need to analyze the current status of low-carbon energy transitions in Vietnam.	To review the publications to find criteria and apply MCDA to rank developed polices	Vietnam
[82]	Qualitative Comparative Analysis	Need to investigate the paradox between short-term policy and low-carbon energy transition.	To conceptualize a framework for temporal energy justice	India
[83]	EIRIN model	Need to remove the subsidies to move toward low carbon energy transition	To study the effect of removing fossil fuels' subsidies on energy transition	–
[84]	Mathematical model and scenario planning	Need to study building retrofitting as one of the factors affecting low-carbon energy transition.	To propose a decision support system to evaluate the energy efficiency measures' profitability	Spain
[85]	Qualitative Comparative Analysis	Lack of connection between circular economy and low carbon energy transition	To link circular economy to low carbon energy transition through non-energy use (NEU)	–
[86]	LEAP-Linear programing	Need to analyze various transitions scenario	To propose a forecasting model to analyze the transition scenario	Botswana
[87]	Agent-Based Model	Need to understand the possible energy transition pathways	To integrate human behavior with energy systems using an agent-based model	–
[88]	multi-level perspective approach (MLP)	Need to study the possibility of transitions toward a sustainable future	To analyze Res in Bulgaria over ten years	Bulgaria

- Institutional pillar: It comprises challenges affecting decisions, policies, and strategies or is caused by them. Although socio-technical transitions require new supportive policies, anti-innovation policies might hinder the low-carbon energy transition, similar to public resistance to change and investment risks. For instance, the wind turbine industry requires domestic market demand and research and development support, or export-oriented manufacturing policies are vital for PV manufacturing. Also, short-term policies are barriers to the low-carbon energy transition. For instance, countries with enriched non-renewable resources tend to give more energy subsidies to support their political parties; however, low fossil-fuel prices impact the pace of the low-carbon energy transition. Furthermore, reformation and transition are two faces of a coin; thus, reformation is required for a successful low-carbon energy transition; however, reformation might cause conflicts and, subsequently, resistance to changes. Constant conflicts throughout the policy development stages are possible, such as conflicts in determining tariffs, affecting investment returns.
- Technical pillar: It comprises challenges influencing infrastructures, technology development, and technical standards. The technical shift is inevitable in the low-carbon energy transition to affect the global energy budget on climate change, sequester carbon emissions, and reduce or stabilize the global average temperature. As a result, sustainable energy systems are jointly approaching standards, technology, and infrastructure. For instance, some Technical changes that should be implemented are adopting low-carbon technologies to improve energy efficiency at the production level and energy saving on the demand side. However, a lack of Technical standards could hinder the developing and adopting of new low-carbon technologies at the desired pace, meeting local and global requirements according to international agreements, such as the Paris agreement.

Table 8
Studies published in 2020.

Author (s)	Methods	Research gap	Study aims	Case study location
[89]	Qualitative Comparative Analysis-network visualization	To study the effect of network governance on low-carbon transition and transition management (TM)	To compare energy transition networks in three countries	UK, Germany, Bulgaria
[90]	Qualitative study: individual and group interview	Need to investigate the political aspects of low-carbon energy transition	To employ a political framework to investigate the unfolding transition politics in new energy vehicle (NEV) development	China
[91]	dynamic simulation model, scenario planning	Need quantitative analysis to provide a decision-support system for policymaking.	To study the energy strategy concerning the low-carbon energy transition (2016–2030)	China
[92]	the multi-level perspective (MLP) and agent-based modeling (ABM)	Need to propose a theoretical and practical framework for the low-carbon energy transition process	To apply two new methods for a detailed and more profound analysis of low-carbon transitions	–
[93]	A mathematical model named CRESOM	Need to find the best transition pathway	To analyze and find the proposer pathway for the low-carbon energy transition	China
[94]	Interview and survey	Need to investigate energy justice in transition	To integrate energy justice into the energy transition project in China	China
[95]	Mathematical models and scenario planning	Need to cope with the targets of climate change mitigation	To provide some pathways and identify the challenges to low carbon transition	China
[14]	Qualitative Comparative Analysis, interviews	Need disruptive innovation to increase the speed of transition	To bridge disruptive innovations and system-level transitions' concept	UK and Germany
[96]	Static and Dynamic Panel	Need to study the effect of public investment	To study the effect of public investment in 17 countries	–
[97]	Scenario planning	The low-carbon infrastructure needs sand which is a limited resource	To map the projected investments in low-carbon infrastructure	–
[98]	Computable general equilibrium (CGE) model	Need to evaluate the risk of the low-carbon transition	To assess the implementation risk of energy transition in the steel and electricity sectors	Austria
[99]	Cluster analysis approach	Need to study the social acceptance of the low-carbon energy transition	to identify energy visions toward low carbon energy transition	UK
[100]	Global Change Assessment Model (GCAM) model, Scenario planning, survey, and interview	The environmental, social, technical, political, and economic risks of low carbon energy transition must be investigated.	To explore the barriers between scientists and stakeholders concerning climate change alleviation aspects	USA, EU27, Canada, Japan
[11]	Qualitative Comparative Analysis, interviews	Need to have pathways for low-carbon energy transitions	To draw a pathway for energy transitions in Spain and develop guidelines for its future	Spain
[101]	mixed-integer linear programming (MILP) model	Need to optimize the storage systems	to analyze the possibility of installing new renewable energy plants	Italy
[8]	Survey	Need to investigate the potential of energy transition	To analyze the current situation of the energy sector in Ghana	Ghana
[102]	multinomial logit model (MNL)	There is no comprehensive evaluation of citizens' potential to co-finance	To investigate the European tendency for investment in the low-carbon energy transition	EU28
[13]	Case study	Need to understand how low-carbon energy transition could be enabled through REs.	To study the contribution of the helix mechanism to the future electricity system	Greece
[103]	scenario-based analysis	The climate change policies' impacts on North Africa's current energy system must be simulated.	to evaluate the energy transitions' sustainability in the North African economies	North Africa
[104]	LEAP	Need to study long-term planning and forecasting of energy demand and supply.	To propose a forecasting model and evaluate various scenarios for the energy sector in Chile	Chile
[105]	linear programming	Need to determine Cooper's impact on the low-carbon energy transition.	To propose a mathematical model to evaluate the copper availability due on 2050	–

3.1. Social challenges

In the following, social challenges are presented in detail, including public acceptance and engagement, public education and awareness, behavior changes and resistance, energy justice, labor transition, and energy security.

Public acceptance and engagement. The role of states in increasing engagement transition processes was not addressed adequately [138,139], and the critical role of public and democratic engagement in low-carbon energy transition has been disregarded in many studies [34,140]. Widespread public acceptance is vital to promote an energy transition toward a low-carbon system [15,87]; also, public engagement increases the reliability of low-carbon technologies and, in general, the acceptability of low-carbon energy transition [13,141]. Behavioral change is needed for public acceptance, stimulating

Table 9
Studies published in 2021.

Author (s)	Methods	Research gap	Study aims	Case study location
[106]	Survey and interviews	Need to deal with injustice transition	To analyze consumers and energy injustices in three low-carbon transitions	Germany, Norway, Great Britain
[1]	Comparative analyses	Need to consider justice in transition	To analyze the just low carbon transition in authoritarian countries	China
[107]	Interviews	Need to consider justice in transition	To link energy justice, low carbon transition, and sustainable development	Vietnam
[108]	Comparative analyses	To link energy transitions, low-carbon transitions, and socio-technical change	To provide a general framework for the low-carbon energy transition	–
[109]	Comparative analyses	To study whether low-carbon energy transition could alleviate the energy poverty	To study the natural gas consumption impacts on China's energy poverty	China
[110]	semi-structured interviews	Need to reconstruct industries in the energy transition	To study the impact of industrial restructuring on the labor market	China
[111]	Interviews	need to consider social resistance and the government's role in the transition	To study a failed solar project to discover the social resistance's role.	China
[1]	Infrastructure-Based Optimization Approach	Need to find an affordable pathway to transition	to investigate transition costs with various low-carbon targets	China
[112]	Data Mining and Regression	Need to evaluate the public acceptance	To investigate public sentiment concerning solar energy	USA
[113]	Comparative analyses	Need to develop infrastructure in transition	To investigate the share of solar energy in Portugal	Portugal
[114]	Interviews	To understand the effect of direct investment on the energy transition	To study the direct and flow-on impacts of a direct-funding on low-carbon transition in shanghai	China
[115]	Stock-Flow Consistent model	The financial risk of energy transition	To understand the conditions under Green Supporting Factor (GSF) and global Carbon Tax (CT)	–
[116]	Retrospective analysis	Need to have specific strategies for transition	Ti studies the challenges to the energy transition	–
[117]	Content Analysis	Need to consider Energy security, equity, and sustainability	To investigate the energy transition doctrine in Russia	Russia
[118]	Content analysis	Need to analyze political conflicts surrounding low carbon energy transition and climate change.	To investigate the responses of crucial actors to climate-energy consultations concerning the EU emissions trading system (ETS) and renewable energy directive (RED)	EU
[119]	Survey and MCDA	Land scarcity is one of the main factors affecting REs	to identify methods that could contribute to mitigating land scarcity	the Netherlands, Belgium, Denmark, Germany, Latvia, and Sweden
[120]	Mathematical model	Need to study the impacts of the energy transition on the labor market	To forecast the loss of labor caused by the low-carbon energy transition	Poland
[121]	semi-structured interviews	To Study the role of law in the low-carbon energy transition	To study the energy transition law in Saudi Arabia from environmental and political perspectives	Saudi Arabia
[122]	Comparative analyses-MCDM	Need to consider justice and poverty in transition	To propose a framework to evaluate energy justice in transition	Lithuania and Greece

active engagement in a decentralized energy system [142]. Furthermore, solar and wind energy may encounter societal acceptability challenges [54,143,144]; however, energy planning might not begin with increasing public engagement and participation [99,145]. Also, public networks foster interaction and cross-sectoral cooperation among diverse organizations, improving decision-making and increasing public engagement [89,146].

Additionally, consumers' roles in the current energy system must be more reactive, adopting new low-carbon technologies by implementing them into daily lives [62]. [147] mentioned that acceptance by the community is a severe challenge associated with influencing political goals. Moreover, public support and social acceptance are significantly helpful in facilitating energy transition [92,148]. Also, Ryghaug et al. (2018) Mentioned that the energy transition requires significant public support, starting from public acceptance; however, public acceptance is far beyond simple acceptance or rejection. Also, it is believed that public support and acceptance of renewable energy may influence renewable energy policies, promoting renewable energy deployment [112]. Social acceptability issues will differ in socio-cultural settings. The low-carbon transition includes social shifts in all circumstances required to achieve an equitable transition [116].

Public education and awareness. Public education is critical for energy transition as it increases public awareness. The energy transition information must span spatial and temporal dimensions from small

Table 10
Studies published in 2022-23.

Author (s)	Methods	Research gap	Study aims	Case study location
[123]	Statistical methods	Economy concerns might impact the energy transition.	Investigating the impact of economic recovery after the Covid-19 pandemic on the low-carbon energy transition.	Worldwide
[124]	Multiple objective linear programs	Identifying how efficiently to mitigate greenhouse gas emissions and supply energy is required.	Identifying an optimal mix of various types of low-carbon energy transitions between developed and emerging countries	Worldwide
[125]	Mathematical models	Identifying the drivers of the low-carbon energy transition	Figure outing the incentives for choosing green or the low-carbon energy transition.	China
[126]	Transcendental logarithm production model	The role of technology must be considered more in adopting the low-carbon energy transition.	To estimate factor output and energy substitution among REs, oil, and gas.	North African countries
[127]	DEA	The impact of environmental regulations on renewable energy development must be analyzed.	To assess environmental regulations using a novel integrated method.	China
[128]	LEAP model, Case study	Climate change needs to promote a low-carbon energy transition.	Developing a comprehensive planning method.	China
[129]	DEMATEL	Offshore wind farms have faced many challenges needed to be analyzed.	Developing a multi-criteria method to examine challenges to adopting offshore farms.	India
[130]	System generalized method of moments	The low-carbon energy transition's social, economic, and environmental consequences must be analyzed.	Developing a novel comprehensive measure of common prosperity.	China
[131]	Synthetic control method	To figure out whether the low-carbon energy transition impedes air pollution.	Analyzing the impact of coal-to-gas policy on air pollution	China
[132]	Qualitative method	Environmental concerns must be considered in adopting the low-carbon energy transition.	Investigating the environmental policy dimensions of the low-carbon energy transition.	Brazil
[133]	Mathematical models	The low-carbon energy transition might reduce energy intensity.	Providing some policies for improving green innovation as it is caused intensity reduction	Worldwide
[134]	SEM	To measure public support for adopting the low-carbon energy transition	The willingness to pay of rural households is measured.	China
[135]	Qualitative method and literature review	To consider the change of business model innovation interactions with their wider environment.	Exploring the systems through which business activities interact with social policy aims.	–
[136]	Method of Moments Quantile Regression	ASEAN countries use more non-renewables, making the transition more difficult.	analyzing the impact of sustainable energy technologies, carbon finance, population growth, and carbon taxes on energy transition	ASEAN
[137]	Mathematical models	Covid-19 reduced the pace of energy transition.	To propose a road plan for moving toward a low-carbon system after Covid-19	China

geographic scales—individual companies and neighborhoods to cities and states [15,129]. Sharing helpful information and knowledge regarding low-carbon energy transition through public campaigns, energy-related websites, and standards is necessary [29]. Moreover, social movements can potentially boost policy development [149], demonstrating how emerging interests may raise public awareness and encourage decision-makers and companies to benefit from a low-carbon strategy [30]. [81] mentioned that a lack of awareness regarding the country's energy status is a barrier to the low-carbon energy transition reinforcing a need for public education. Also, a lack of shared awareness about energy security due to fossil fuel availability has resulted in sustainability [89]. [129] concluded that lack of awareness is an influential challenge to adopting offshore wind farms.

Moreover, It is noted that weak public awareness and inadequate training are barriers to adopting renewable energies [86,150]. Also, social learning is more feasible in societies with open, transparent, and participatory policymaking procedures and diverse professional and social networks [2]. Besides, there is a dichotomy between stakeholders' attitudes regarding decarbonization and the low-carbon energy transition, encouraging policymakers and leaders to increase awareness by improving public education [57]. Also, Siciliano et al. (2021) mentioned that improved education and training are needed for people impacted by low-carbon technologies. As a result, knowledge sharing and increasing awareness change behavior to achieve a low-carbon energy system [151].

Behavior change and resistance. Low-carbon technologies can enable the development of more responsive infrastructure to environmental and social imperatives; however, they also threaten critical revenue from affluent consumers that cross-subsidize electricity for low-income people [152]. In addition, widespread changes in consumers' energy usage are required to achieve a low-carbon energy future, and technical change is insufficient to achieve a low-carbon energy system. Behavior changes mean adopting low-carbon activities, such as less demand for household heating, reduced Vehicle Miles Traveled (VMT), and adopting low-carbon modes of transportation [29]. The magnitude of required change, the length of time, and the uncertainty associated with energy are critical feathers of the low-carbon energy transition, making low-carbon energy transition more difficult [15]. Nevertheless, the fundamental changes from the low-carbon energy transition need decades of policy development as social structures are gradually reconstructed in a low-carbon manner [153].

Furthermore, Technological innovations, appropriate policies, finance, and a systemic change in core behaviors, practices, and policies should be considered to have a low-carbon energy transition [59]. For example, transitioning from gasoline-powered to electric vehicles would require a shift in technology and customer preferences [154]. However, fossil fuels are necessary for human survival and economic prosperity. This distinction is commonly missed in the debate between proponents of the immediate need to alter human behavior and those seeking to preserve and sustain present socioeconomic arrangements [47]. Also, Holtz et al. (2018) confirmed that *Regime change* is needed for the low-carbon energy transition, which is done through consumer behavior, institutions, and infrastructure changes. On the other hand, *regime resistance* to developing low-carbon energy systems means that incumbent utilities might try to form a public debate around the negative impacts of low-carbon energy to halt or slow the low-carbon energy transition [111].

Energy justice. It could be defined as a worldwide energy system in which the advantages and disadvantages of energy services are distributed fairly among users [50,64]. Successful low-carbon transition requires a standard set of views, values, skills, interests, relationships, and resources grounded by knowing the need for sustainable routes [82,155]. Failure to promote public engagement may result in less representative and responsive policy decisions, generating societal tension and hatred and increasing inequality and exclusion [79,156]. Moreover, there are four types of justice, including *procedural* [52]– participation in decision-making processes that promote equity; *distributional* [52]– the balance of environmental advantages and disadvantages; *recognition* [157,158]– the fair representation of persons who are not threatened physically and are guaranteed full equality political rights; *cosmopolitan*- All humans deserve just energy and are morally equal [159,160]. Furthermore, justice energy literature acknowledges "just energy transition," which places social justice as central to energy transformations. Its goal is to avoid the upcoming phase of energy transitions from generating new social inequalities to exacerbating existing ones [1,122].

Decision-makers can directly consider energy justice while establishing new energy technologies. Increasing attention to procedural, distributive, and recognition of energy justice details might help "equalize" and "democratize" decarbonization measures [46,73,79]. [11] mentioned that energy justice is a niche for innovative discourses to advance alternative, participatory agendas and more democratic energy systems and decision-making. Stakeholders have clarified justice standards as *reconversion*: promoting industrial redevelopment in afflicted areas; *participation*: promoting greater engagement in the energy system; *compensation*: healing harm was done to individuals, society, investors, and nature; *distribution*: increasing the proximity of energy production to the point of consumption; *transparency*: presuming more clear decision-making procedures [37]; *plurality*: includes a diverse range of performers, perspectives, and decision-making situations [37].

Labor transition. The transition from coal could happen through a significant energy transition agreement signed by labor, unions, and governments to facilitate such a transition. It will boost coal mines' reformation and emphasize re-skilling employees to facilitate a just transition to adopt socioeconomic factors [11]. However, although the low-carbon energy transition may create several job openings in green industries, the overall effect on the labor force ultimately relies on the likelihood of people leaving the non-green sector to find work elsewhere. Optimistically, if all new green industry jobs were filled exclusively by workers who quit neutral industries, the transition's net inflationary effect would be a combination of job creation in green industries, job loss in neutral industries, and job loss in non-green industries [120]. Furthermore, there are constraints on dynamic labor markets since restrictions prohibit employees from transitioning from the current energy system to a low-carbon energy system due to skill shortages or mismatches, regional relocation challenges, and demographic issues [85]. Also, Bai et al. (2021) concluded that low carbon energy transition affects employment indirectly; therefore, labor transition needs more attention as perhaps the most significant societal consequence.

By renewing the structural workforce toward low-carbon industries, the impact on labor market regulations may help achieve the low-carbon transition. In this perspective, it is crucial to investigate whether REs technologies require more labor to deliver the same energy level as fossil fuels when jobs in associated activities such as equipment production, operation and maintenance (O&M), installation, and fuel supply are included [61]. [72] concluded that changes energy system would significantly impact labor demand across the economy. It is predicted that significant linkages would exist between employment growth and the requirement for various skill levels. Additionally, it is clear that companywide skill demands – both direct and indirect impacts the economy – can alter the labor market' need, which has consequences for labor market strategy in the low carbon transition. It should be noted that labor unions have worked to affect the allocation of advantages and disadvantages within energy systems by lobbying for and obtaining equitable distribution, recognition, and involvement primarily within current energy systems.

Energy security. A significant problem is ensuring countries move towards energy transitions considering energy equity and security [58]. Energy security is defined as the effectiveness of the primary energy mix from domestic and international sources and infrastructure dependability. Also, energy equity is defined as the affordability and accessibility of energy supply to all communities [161]. However, sustainability and affordability are already included in energy security, resilience, availability, and governance [162]. As a result [163], proposed four "Rs" to recognize and deduce what comes within energy security quickly, including *reviewing* available energy sources and suppliers, energy services and infrastructure, secure energy supplies and intensities; *reducing* energy demand through energy efficiency and conservation; *replacing* vulnerable energy supplies through altering infrastructure and diversification; *restricting* new demand to secured sources.

According to the four "Rs," achieving energy security with sustainability and equity is challenging since it is needed to improve technologies, boost the local and global economy, and manage energy demand and supply [161]. [117] divided energy security into two categories: the security of supply and demand. Supply security ensures enough, dependable energy supply at reasonable rates and without jeopardizing critical national priorities and objectives. Demand security encompasses consumer availability, pricing fairness, and energy flow security.

3.2. Economic challenges

Economic challenges are presented in detail in the following, including incentives and investment risk, mitigation and adaptation costs, and subsidies.

Incentives and investment risk. There is a significant imbalance between the required funds to move toward low-carbon technologies and the available funds [164,165]; thus, increasing funds is required to fulfill climate change mitigation and adaptation requirements [60,64,102]. However, disruptive innovations could reduce the cost of RE technology adoption but could increase the maintenance cost of the current energy grid [68,152]. Also, off-grid renewable technologies are relatively cost-effective for delivering advanced energy sources to rural households and may provide opportunities for improved development [9]; however, significant investment is required [28,51,103]. On top of that [62], concluded that developing REs technologies could temporarily decrease labor productivity and GDP; however, the duration and intensity depend on the investments required for REs technologies. Furthermore, more financial incentives are needed to motivate the civic energy sector in market-based economies [35]. Also, authorities should provide adequate incentives for low-carbon technologies to deal with the policy resistance and to represent a steadfast commitment to decarbonization [65].

Also, many challenges to low-carbon energy development remain without international cooperation and private investment [32,81]. However, non-profit investors or individuals do not have enough incentives to participate in renewable energy; even their engagement in renewable power is sometimes strongly discouraged [166]. For instance, solar panels' environmental tax owing to the incorporated carbon in the manufacturing system, the low feed-in tariffs, and the meager energy unit price established by the state are indirect or direct disincentives [76,89]. Also, governments should provide commercial incentives for investors to reduce investment risk since it is required for governments to demonstrate their contributions to low-carbon energy development when it comes to public money investment [37,84,115]. Furthermore, it is universally acknowledged that, first, the majority of these investment projects must be financed by private funds [8], and second, conservative mitigation initiatives must be implemented to achieve such a massive increase in private investment, which implies a consistent shift in private investment from current energy system to a low-carbon system [45, 96].

Mitigation and adaptation costs. The term "mitigation costs" refers to the policy expenses associated with meeting climate goals. Thus, it is critical to define a realistic and cost-effective low-carbon energy transition to prevent the most severe effects of global warming [100,167, 168]. Also, budget constraints and infrastructure privatization have adversely affected states' capacity to drive climate change mitigation and adaptation efforts [89]. Also, improving performance and cost reductions across technologies and their implementation in diverse contexts is complicated and widely covered in Technological innovation and socio-technical transition [147]. Furthermore [91], mentioned that the energy transition costs include operation, construction, various fuel types, maintenance, and the social cost of carbon emissions. Also, there is a critical need for new generations of biofuels to mitigate climate change; however, the higher cost of advanced biofuels may result in high mitigation costs for society [80].

The low-carbon transition will entail enormous energy system transition costs due to the complexity of energy systems characterized by novel technologies, carriers, spatial-temporal elements, and particularly high-investment infrastructure [93]. As a result, infrastructure investment is crucial because of large-scale renewable energy development. Also, phasing out fossil energy might result in system transition costs [55]. Therefore, Cost reduction is desirable but difficult since there is no one way to achieve a low-carbon energy system transition. Each way includes vast transition policies associated with different timing and speed, which would affect transition costs, despite all ways having the same goal [62].

Subsidies. Subsidies for fossil fuels have a significant environmental impact, stimulating renewables adoption, labor transition, and the low carbon transition [67]. Cutting down subsidies to minimize energy consumption and greenhouse gas emissions is needed. It is widely believed that fossil fuel subsidies encourage excessive energy use; eliminating them would reduce energy-related CO_2 emissions [95]. Also, Shem et al. (2019) mentioned that one of the impediments to renewable energy growth is the low price of coal and subsidies, which create an uncompetitive sector for more sustainable alternatives. However, it is possible to support the low-carbon energy transition through governmental support and subsidies; therefore, subsidies and tax credits effectively balance various enterprises' viability and market costs [92]. Furthermore, fossil-fuel costs are believed to be unpredictable and likely to continue rising, eventually making sustainable low-carbon energy more appealing. Thus, reducing subsidies would decrease the demand for fossil fuels, making low-carbon energy more feasible [28]. Additionally, the government must continue to reform the energy market and avert a resurgence of fossil fuel energy subsidies for energy products [83].

3.3. Environmental challenges

In the following, environmental challenges are presented in detail, including land acquisition, waste and pollution, and natural resource consumption.

Land acquisition. Land acquisition on a large scale is needed for the renewable energy transition, a distinguishing aspect of the current global land rush [16]. Ultra-mega solar parks require thousands of acres [169]. Despite these substantial financial investments, suitable lands are rare since they must have the appropriate size, be available, and be located in areas with solid energy demand [77]. Only government-controlled lands, such as 'wastelands' or 'marginal' lands, could meet the mentioned requirements. Land grabs are critical to the global land rush toward a low-carbon transition [170]. Land grabbing is a term that refers to the practice of enclosing enormous areas of land [171]. Moreover, "green grabbing" is another form of land grabbing in which land and natural resources are dispossessed under sustainable development [172]. Furthermore, for instance, solar PV power plant development has altered land-use patterns resulting in new land-use disputes [62]. Citizens may assert that the plant's visual effect breached their right to the landscapes, receive compensation for the inflationary pressure of property close to the site, and request that their land be reclassified under the plant's land [113].

Moreover, protecting high-biodiversity regions or places in danger of losing carbon pools may necessitate land-use restrictions, sometimes with economic compensation for landowners who forfeit revenue opportunities [42]. Also, it is predicted that the European Commission's plan for a low-carbon economy by 2050 emphasizes the importance of developing biofuels technologies to combat climate change, thereby bringing up other sustainability concerns associated with biofuels in general, such as biodiversity water management and land-use change [80,117]. [119] stated that land scarcity is a barrier to progress toward a low-carbon economy associated with the relatively high rising competition between land-use priorities, especially in the EU, such as the Netherlands.

Waste and pollution. The main challenge in waste and pollution management is nuclear energy waste—public concerns about radioactive waste [31]. Also, biofuels and biomass, considered alternatives to fossil fuels, could emit polluting substances, including carbon monoxide, through photosynthesis. On the other hand, the plants that provide biomass could collect the same quantity of CO2 produced by fossil fuels [42]. Also, there is a growing market for lithium-ion batteries (LIBs) for electric vehicles and auxiliary energy storage devices to support renewable sources. Recycling LIBs would not be a pollution-free activity. Also, pyrometallurgy is a high-energy process that generates GHG emissions and poisonous fumes or hazardous waste that must be landfilled [173]. However, one of the most severe risks linked with landfilling and unlawful processing is the formation of leachate: this substance is created due to numerous biological and chemical deterioration processes, as well as rain seeping through garbage [174].

Natural resource consumption. Mineral resource reliance is an illustrative example of the world's energy transition difficulties. Research has shown a shortage of diversity in raw material resources, such as copper, cobalt, and lithium.

[105] mentioned that global copper demand growth is projected to strain available copper production capacity further. In this respect, the

massive growth in copper usage should be accompanied by copper recycling. Also, it is believed that significant hazards arise primarily due to the growing importance of storage, which results in an increase in demand for natural resources, resulting in unavoidable environmental effects, such as mountainous areas for hydro storage and lithium extraction and sand for construction [97,98]. Also, dangers would arise due to incorporating carbon capture and storage (CCS), and the influence of climate change may have an effect on the availability of renewable energy [80]. In addition, long-term but low-cost supplies are crucial for implementing biomass power plants, and insufficient biomass resources constitute a barrier to low-carbon energy adoption [95].

3.4. Institutional challenges

In the following, institutional challenges are presented in detail, including short-termism, anti-innovation, and conflicts and reformations.

Short-termism. One of the barriers to low-carbon energy development is short-term policies ratified by governments to survive politically and economically [43,49]. For example, in petrostates like Iran, Kuwait, and Iraq with high budgetary break-even points (BEP), ensuring short-term revenue is critical for political positions [175]. Moreover [89], mentioned that short-termism is a public policy formulation and execution, restricting the alternatives for integrating short-term decisions with long-term goals. In addition, government engagement in the energy transition is most likely to address the long-term external cost of energy usage rather than delivering a short-term private advantage [2].

Therefore, decision-makers must struggle with technical uncertainty and short timelines incompatible with long-term system transformation. In contrast, it progresses beyond incremental interventions to substantial structural change within socio-political restrictions [147,176]. Furthermore, cooperation between governments and parties will be critical to establishing a path to a low-carbon energy transition; thus, long-term collaboration and partnership provide significant prospects for accelerating technological and system innovation, scaling up collaboration, and increasing financial availability [92,177].

Anti-innovation policies. Innovative policies are required to support the low-carbon energy transition to reconfigure the current status of energy sectors [40]. Also, Chen and Kim (2019) mentioned that anti-innovation policies could hamper innovations, similar to public resistance and investment risks [104]. mentioned that appropriate renewable energy policies under international support must be applied to mining, transport, and industry sectors to decrease emissions dramatically on the demand side. In addition, although carbon pricing is usually regarded as the fundamental of sustainable climate mitigation policies, there is also a necessity for innovative policies, such as subsidies, regulations, and information supply, to boost innovation and eliminate barriers to low-carbon paths [15]. Also, policies must incorporate measures that promote renewable energy technologies to facilitate the transition to a low-carbon economy [81]. In other words, the government actions should be sustained over time, so all policies should always be coordinated to meet low-carbon energy transition targets [55,111,116,178] also confirmed that the central government entities play a critical role for solar PV in China, and Bracco (2020) confirmed that new policies are needed to support electricity storage systems (ESS) in the North of Italy. Also, Werner and Lazaro (2023) concluded that implementing climate and sustainable energy policies needs political will and public support.

Conflicts and reformations. Transition governance is a multi-faceted, multi-actor, multi-level, and multi-phase governing process that enables systemic transitions of socio-technical systems toward sustainability [118]. Therefore, gradual reformation is needed, especially in authoritarian countries, which generally maintain rules, causing conflicts in transiting to low-carbon energy systems [90]. Constant conflicts may be observed throughout the various stages of policy development, such as the political conflict in determining tariffs, which directly affect investment returns [63]. Typically, states play a significant role in transition governance, widely described in its democratic form as the triangle of executive, legislative, and judiciary authority [88]. The state's tasks in the transition governance process include regulating, coordinating, providing, introducing, managing, and safeguarding [179]. The constraints on preserving policy credibility are underscored by explicitly outlining the degree of flexibility with which regulations can be (re)designed [180], particularly when such changes contradict institutionalized forecasts of future policy changes in key aspects of the policy mix [65]. On top of that, public awareness, the macro economy, and policy channels may be mutually reinforcing since policy reforms may raise public awareness, influencing consumer decisions [30].

3.5. Technical challenges

In the following, institutional challenges are presented in detail, including a lack of technical standards and infrastructure.

Lack of technical standards. The low-carbon energy transition will need the widespread adoption of novel technologies, regulations, and policies, such as carbon pricing regimes and regulatory standards [15], or sometimes even fewer regulations concerning renewable energy development [81]. A comprehensive set of standards and regulations pushes the energy supply to follow a predetermined path [92]. Also, Gössling and Scott (2018) mentioned that many stakeholders had confirmed a lack of standards hindering the low-carbon energy transition, and [117] concluded that the required regulatory frameworks are underdeveloped, impeding the implementation of novel technologies in the energy industry, including distributed electric energy, renewable energy, and information technology. In addition, Failure to include all potential influencing operations and toxic pollutants in decision-making and legislation enables legal waste production [98]. Also, while environmental guidelines are focused on gaseous emissions, it is theoretically conceivable for enterprises to change their processes to release toxins in plenty of other sources, such as the air or groundwater [121].

Lack of infrastructure. System transition requires a fundamental change in infrastructures, politics, and customer behavior [44,154]. For example, transitioning from gasoline-powered automobiles to electric vehicles would involve a shift in automotive innovation and technology and an entirely new infrastructure equipped with electric charging points [59]. Changing demand for renewable energy threatens the grid's stability and flexibility because an innovative energy infrastructure seems to be a precondition for the energy transition, which entails several implementation risks [98]. On top of that [89], concluded that the privatization of infrastructure had reduced the capacity of states to manage climate change mitigation and adaptation efforts; however, short-term emissions reduction requires technical changes [71], including new infrastructure; and social changes, such as overcoming fragmentation to provide new infrastructure. Also, Kuamoah (2020), another impediment to renewable energy penetration is a lack of infrastructure, notably aging and undeveloped national grid networks; however, decisions regarding which resources to focus on and where to develop new infrastructure may result in unequal regional economic development and energy poverty at the local and household level [36,39]. Renewables need energy storage alternatives to match energy demand reliably at various time scales [181].

As mentioned, seventeen challenges to the low-carbon energy transition have been identified in the present research, illustrated in Fig. 4.

4. Conclusions

The low-carbon energy transition is a socio-technical transition requiring decision-makers and researchers to deal with many social, economic, environmental, technical, and institutional challenges. To this end, decision-makers and researchers should know the challenges and how they should be tackled to accurately follow the timelines

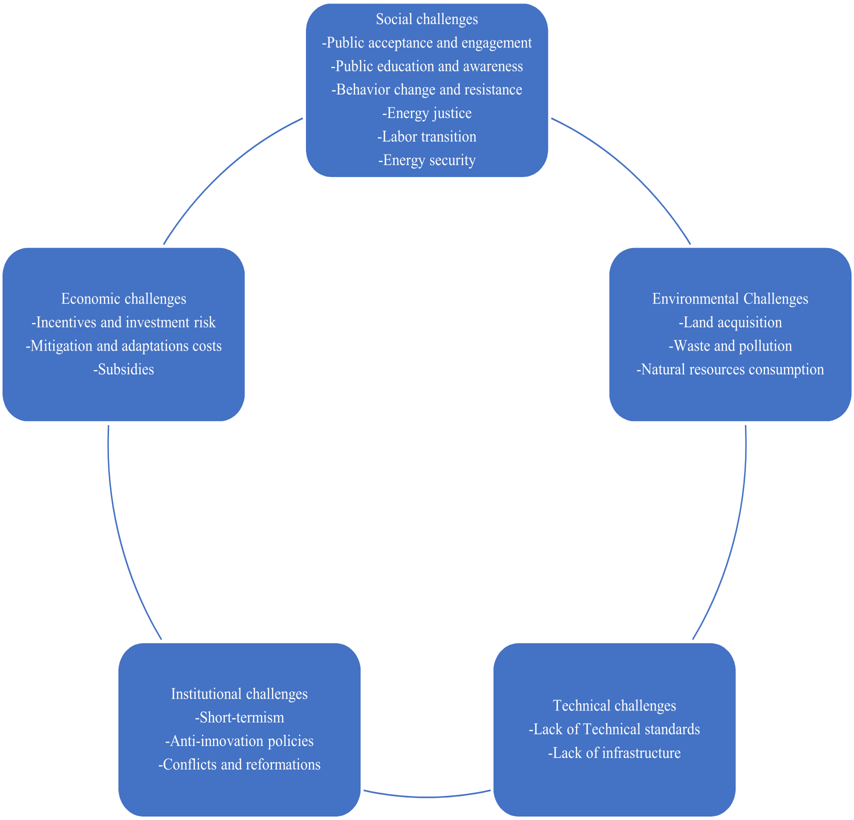

Fig. 4. The framework of challenges to the low carbon energy transition.

presented in global agreements, such as the Paris agreement. Therefore, the present study conducted a systematic literature review using an integrated methodology to review 123 publications out of over 1000 found articles on the low-carbon energy transition to propose a comprehensive framework addressing social challenges, such as public acceptance and engagement, public education and awareness, behavior change and resistance, energy justice, labor transition, and energy security; economic challenges, such as incentives and investment risk, mitigation and transition costs, and subsidies; environmental challenges, such as land acquisition, waste and pollution, and natural resources consumption; and institutional challenges, such as short-termism, anti-innovation policies, conflicts and reformations; technical challenges, such as lack of technical standards, and lack of infrastructure. On top of that, many researchers have applied various qualitative and quantitative methods over the years, motivating the present study to provide information regarding applied methodologies, case study locations, and obtained results.

Furthermore, the publication rate on the low-carbon energy transition has grown dramatically since 2016; thus, it could be concluded that the Paris agreement, one of the most influential agreements in climate change mitigation, has significantly motivated researchers to study the low-carbon energy transition increasingly. Also, it could be concluded that transiting towards low-carbon energy systems is a complex and inter-connected process in which scientific, political, social, etc. interactions; thus, all influential factors should be considered in developing policies, agendas, or even conducting research; otherwise, the results would not be effective enough to reach the climate change mitigation's goals. Results indicated that technologies that enable enhanced or new services are critical in catalyzing a transformation, even if they are initially prohibitively expensive. Governments are frequently absent during such changes. The government's engagement in the energy transition is most likely, as it is costly and motivated by the necessity to address the long-term external cost of energy usage to the public rather than delivering a short-term private advantage. Markets alone will not affect the necessary behavioral changes in the timeframe required. The apparent lack of time left for the worldwide low-carbon transition also separates it from previous regime changes and makes this transition particularly difficult. As a result, governments must devote themselves to transforming technologies and behaviors to improve energy production technology because history demonstrates that improvements in end-use technologies drive most energy transitions. Nevertheless, changing end-user behavior to achieve the benefits of technology innovation needs a significant institutional transition in most societies.

4.1. Research agenda

Furthermore, many research gaps in the low-carbon energy transition should be studied according to the future directions provided by researchers over the years. The present study classified them into *replication* studies and *new avenue* studies. The new case studies group devotes to those studies in which a new framework or analyzing model was applied to case studies; then, they also recommended that to reapply their study to another case study. The replication studies are presented in the following.

- Recommendations for applying multicriteria decision analysis models under fuzzy sets:
  - o Nikas et al. (2018) recommended applying the integrated FCM-DSGE-BSAM method to the energy mix and pricing strategy affecting energy security; however, FCM could deal with both quantitative and qualitative problems; thus, it is possible to include social, environmental, institutional, and technical factors to cognitive maps to make a comprehensive model of the current status of the low-carbo energy transition; also possible to run the model under various scenario to see the results under various assumptions.
  - o Shem et al. (2019) recommended applying the MCDM method to evaluate the policies' efficiency by stakeholders; however, the MCDM method could include a variety of factors related to all identified challenges, not only institutional or pollical. Also, MCDM methods usually are integrated with fuzzy logic to improve their accuracy and applicability under various assumptions to deal with vagueness and uncertainty in MCDM problems.
  - o Janssen et al. (2020) recommended integrating system modeling with MCDM in dealing with land scarcity issues. Location selections are multi-criteria problems in which MCDM could identify the best location to build solar or wind farms; however, the present study recommends integrating MCDM methods with ArcGIS to improve the obtained results from location selection.
  - o Bracco (2020) recommended finding the optimal location of the storage systems and new renewable power plants. Finding the best location could deal with land scarcity, and the present study recommends integrating MCDM and mapping methods to deal with location selection problems.
- Recommendations for applying assessment models:
  - o Pizarro-Irizar et al. (2020) recommended applying the GCAM model in future studies to study more on GDP and cost impacts caused by climate change. However, adding economic factors to the GCAM model makes future studies novel; it is also possible to add technical and institutional factors to this model to make the obtained results more accurate.
  - o [104] recommended applying the LEAP model in various countries or regions, not just Chile. As mentioned above, applying a model to other countries could make future studies; however, integrating the LEAP model with linear programming is recommended, such as [86] study.
  - o [80] recommended applying to apply Life-Cycle Assessment (LCA) to assess potential environmental effects stemming from the development of next-generation biofuel; however, the present study recommends integrating LCA with other assessment frameworks, such as techno-economic analysis (TEA) and life-cycle costing (LCC) to boost the accuracy and inclusiveness of the future studies.
- o Chilvers and Longhurst (2016) suggested applying their proposed framework under other collective engagement in system change, not just public participation in the energy transition; however, the present study recommends applying the [34] framework to other social challenges identified in this study, making future studies more comprehensive in which most of the social challenges are addressed.
- o Alomari and Heffron (2021) recommended repeating their research in the middle east context, not only in Saudi Arabia; however, the present study recommends applying quantitative methods to analyze collected data, not just descriptive statistics.
- Recommendations for applying mathematical and probabilistic models:
- o [33] recommended applying the proposed linear programming to the rest of Latin America, not just Nicaragua; thus, changing case studies' locations could add novelty to future research, and also, it is possible to compare the results of the future studies with [33] study to figure out how the proposed method works under different conditions and assumptions.
- o Rogge and Dütschke (2018) recommended applying the proposed linear regression model to deal with the issues in other countries, not just Germany, and applying more complex models to capture interdependencies between elements. Linear regression has many extensions, such as marginal models, GEE models, generalized linear models, generalized linear mixed models, and linear mixed models; thus, applying other extensions of linear regression is also recommended. Furthermore, Artificial Neural Networks (ANN) could be an alternative method to regression analysis, making future studies more accurate and novel.
- o Chen et al. (2018) recommended improving the integrated agent-based model by including uncertainties; however, the present study recommends including all identified challenges to the agent-based model to make the model comprehensive.
- o Streimikiene et al. (2021) recommended applying fuzzy Monte Carlo to address uncertainties. As mentioned, fuzzy logic could deal with uncertainties; the present study recommends integrating novel fuzzy extensions with Mont Carlo, such as Fermatean fuzzy sets, making future studies novel.
- o Bachner et al. (2020) recommended applying micro-scale and agent-based models to address investment risks in transiting to low-carbon energy; however, as mentioned, other challenges should be included in the assessment and evaluation models to improve the accuracy and reliability of the obtained results.

Furthermore, some researchers have recommended *new avenues* for future research in the low-carbon energy transition. These studies thoroughly recommend a new research idea, not recommending reapplying a method to other case studies or repeating a study in different locations. New avenue studies are presented in the following.

- Recommendations for more studies on social challenges:
  - o Stock and Birkenholtz (2019) recommended more debates on agrarian labor contributions in solar parks. Labor market transition is one of the social challenges; however, the present study recommends considering all identified social challenges in future studies.
  - o Axsen and Kurani (2012) recommended studying the effect of interpersonal influence on adopting low-carbon products. Public engagement affects the pace of the low-carbon energy transition; however, other social challenges, especially public awareness, should be considered as their interaction affects future studies' results.
  - o Bellos (2018) recommended studying public engagement for innovation and marine energy. All recommendations of [53] align with the results of the present study as the proposed framework included all these factors and more; thus, the present study recommends considering the proposed framework of challenges in future studies.
  - o Zeyringer et al. (2018) recommended studying the impacts of marine energy on job creation, regional development, and new export opportunities. Marine energy is non-carbon energy and affects the labor market; thus, the present study recommends studying the impacts of marine energy on energy security and energy poverty, as these social challenges affect regional development and export opportunities.
  - o Hu (2020) recommended studying how households could adopt new low-carbon technologies in rural areas. Adopting new low-carbon technologies in rural areas could affect energy poverty; thus, the transition could be more successful; however, technology adoption requires increased public engagement and awareness; thus, innovative policies might be developed to overcome the challenges of new low-carbon technology adoption.

- Recommendations for more studies on economic challenges:
  - o Chen and Kim (2019) recommended empirical studies concerning energy transition and circular economy collaboration. The circular economy is a novel following seven principles, including rethink, reuse, recycle, reduce, refurbish, repair, and recover. These seven principles could boost the low-carbon energy transition, especially in waste management.
  - o Hoggett (2014) recommended studying supply chains and low-carbon technologies. Studying low-carbon supply chains could be a novel topic for future research, and the present study recommends studying the circular supply chains in which seven principles of circular economy enable supply chains to be low-carbon.
  - o Hall et al. (2016) recommended investigating how bank-based vs. market-based economies affect the links between capitalism and energy policies. Studying low-carbon energy transition from various perspectives improves the understanding of the current status of the low-carbon energy transition; however, not from only economic perspectives.
  - o Malakar et al. (2019) recommended studying the responsibilities of developing countries toward a low-carbon energy transition compared to advanced economies worldwide. The present study recommends evaluating the performance of advanced counties in dealing with the challenges of the low-carbon energy transition; consequently, other countries could follow those countries to improve their energy systems to reach low-carbon goals.
  - o Schinko and Komendantova (2016) recommended studying the perceived risks' impacts on investing in the low-carbon energy transition. Investment risks are a critical economic challenge to the low-carbon energy transition, affecting the pace of the transition. The present study recommends investigating the relationship between public engagement and perceived risks and their effects on investment.
- Recommendations for more studies on environmental challenges:
  - o Seck et al. (2020) recommended studying water resource availability impacts on raw material demand and the energy transition. Raw materials consumption is a severe challenge to the low-carbon energy transition; thus, the present study recommends studying the role of the circular economy in reducing the required raw materials for transiting to a low-carbon energy system.
- Recommendations for more studies on institutional challenges:
  - o Muinzer and Ellis (2017) recommended more political analyses to elucidate energy transitions; however, the present study recommends including all institutional factors affecting the low-carbon energy transition, not only political analyses. Also, as challenges are interconnected, analyzing the low-carbon energy transition as a whole is recommended to see the factors' interactions and their impact on the obtained results.
  - o Urban and Nordensvärd (2018) recommended studying historical energy transitions in Nordic countries. Studying the background of energy transition might provide some new ideas or solutions to the challenges of the low-carbon energy transition; however, more practical studies in which a specific challenge would be studied are also recommended.
  - o Hall et al. (2018) recommended investigating how future energy policies boost energy justice; However, energy justice is critical to transiting toward a low-carbon energy system. Other significant social challenges, especially energy security, should be considered in policy-making.
  - o Power et al. (2016) recommended developing the conceptual framework considering the relationship between socio-technical transitions and political economy. However, political and economic issues are not the only challenges that need to be considered in studying the low-carbon energy transition; thus, the conceptual framework should include all challenges to the low-carbon energy transition.
  - o [84] studied the political challenges of building retrofitting. Although adopting new low-carbon technologies to the old building might face political issues, retrofitting might pose many social challenges as it directly affects people.
  - o Monasterolo and Raberto (2019) recommended policy-relevant studies on phasing out fossil fuel subsidies. Studying subsidies' contribution to the low-carbon energy transition could be interesting for future research; however, studying the impacts of only one challenge might affect the obtained results, as many other challenges are connected to subsidies and policy-relevant studies.
  - o Huang (2021) recommended doing comprehensive research regarding the governance of urban energy transitions. Studying the low-carbon energy transition in urban and rural areas could identify the specific challenges to low-carbon technologies adoption in these areas. However, the present study recommends measuring the performance of countries in dealing with identified challenges in rural and urban areas to figure out the most critical challenges in these areas in a country.
- Recommendations for more studies on technical challenges:
  - o Baker and Phillips (2019) recommended studying the rapid evolution of disruptive technologies changing electricity governance structures. Disruptive innovation could change the pace and the path of the low-carbon energy transition; however, disruptive innovation requires developing many policies to support innovative technologies.

4.2. Policy recommendations

- How individuals and organizations perceive uncertainties and risks could affect climate policy design. Valuation methods from the social, environmental, economic, technical, and institutional analysis could assist decision-making under uncertainties. Also, mitigation and adaptation could reduce perceived risks, as are complementary strategies.
- Substantial GHG emissions reductions over the next decades could reduce climate risks, costs, and challenges to the low(non)-carbon energy transition in the longer term, building pathways to sustainable development. However, significant changes in investment patterns are required for substantial reductions, and both public and private sectors could have an essential role in financing the low-carbon energy transition.
- There are substantial interactive effects across different energy policy goals, such as just energy, energy security, energy access, and energy availability, and between other technical, social, institutional, and environmental goals. Cost-effectiveness, multi-criteria, and cost-benefit analysis could assist integrated methods for energy policy developments.
- Public education is a social challenge increasing public engagement and reducing public resistance to change. Thus, supportive and clear policies should be developed, especially in the transportation system, considered a carbon emissions resource. For instance, all sectors should provoke employees to utilize low-carbon modes of transportation, such as electric vehicles (EVs), and provide EV charging stations for visitors and employees. Also, a government-verified transportation program should be developed to address carbon emissions reduction.
- Economic instruments like subsidies could be employed across various sectors, including different policy designs, such as tax exemptions, rebates, loans, grants, and credit lines. On the other hand, decreasing subsidies for GHG-related sectors could result in emission reductions, depending on the economic and social context. However, sector-specific policies might work better than economy-wide policies as they could address sector-specific challenges.

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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A novel multicriteria assessment framework for evaluating the performance of the EU in dealing with challenges of the low-carbon energy transition: an integrated Fermatean fuzzy approach

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Abstract

Climate change, global warming, greenhouse gas emissions, and many other reasons have motivated countries worldwide to change energy systems to move toward low-carbon energy systems; however, the low-carbon energy transition has faced many challenges that motivate the present study to identify the challenges and evaluate the performance of the EU according to challenges. To this end, seventeen challenges were identified through a systematic literature review and classified into five groups: economic, institutional, technical, social, and environmental. Subsequently, fifty-three indicators were selected to measure the performance of the EU in dealing with challenges. Furthermore, a Fermatean "Stepwise Weight Assessment Ratio Analysis" method was applied to determine the subjective weight of identified challenges, while the method based on the removal effects of criteria was applied to determine the objective weight of selected indicators. Afterward, the "Technique for Order of Preference by Similarity to Ideal Solution" method was applied to evaluate the performance of the EU in dealing with the challenges of the low-carbon energy transition for 2015 and 2020. The results indicated that energy justice, mitigation costs, land use, and lack of infrastructure are the most significant social, economic, environmental, institutional, and technical challenges. Also, the Netherlands had the best performance in 2015, followed by Germany; in contrast, Germany improved its energy system and took first place in 2020.

Keywords Renewable energy, Green energy, MCDM, Fuzzy logic, Low-carbon technology

1 Introduction

Climate change has been one of the worldwide issues for human beings over the years. The energy sector is the leading source of greenhouse gas (GHG) emissions, mainly brought on by fossil fuel usage in the transportation, industry, and electricity generation sectors. From a global standpoint, low-carbon energy transitions from fossil resources to renewables are a feasible alternative to the dual challenges of minimizing GHG emissions and delivering access to affordable and clean energy in times of human-caused environmental change and accelerated world economies [1]. In other words, the low-carbon transition looks for economic and social prosperity by integrating climate change goals, like reducing carbon emissions with sustainable development objectives. As a result, governments have worked to

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halt the worldwide increase in emissions since the 1990s. Also, the Paris Agreement, adopted in 2015 due to notable international talks, encourages nations to achieve carbon neutrality by 2050. Therefore, all nations are urged to implement an energy transition to address the climate emergency. In order to adhere to the terms of the Paris Agreement and limit the increase in global temperature to 1.5 °C, transitions toward a low-carbon future are essential. To this end, increasing work is being done to speed up the transition to a low-carbon future. However, various risks and uncertainties in the underlying social, environmental, economic, political, and technical elements are associated with low-carbon transition paths. The achievement of climate change alleviation goals could be negatively impacted by inadequate information regarding such uncertainties [2].

Many academics have studied the low-carbon energy transition over the years to identify and deal with its challenges [3]. For instance, it is mentioned that public engagement could increase the reliability and acceptability of the low-carbon energy transition [4]. Also, solar and wind energy might generally face societal acceptability issues; however, public engagement and participation are typical challenges to the energy transition. In addition to technical changes, a shift in energy consumption patterns is essential for achieving a low-carbon energy system. A successful low-carbon transition requires a standard set of values, views, interests, skills, resources, and relationships created by a knowledge of sustainable development. Appropriate policies, systemic change in core behaviors, technological innovations, practices, and finance should be taken into account in transitioning to a low-carbon future [5].

Moreover, energy justice is vital in the energy transition, assisting decision-makers in developing inclusive energy technologies by boosting attention to democratic and equal decarbonization measures [6]. Also, local and global investments are required to deal with challenges to the low-carbon energy transition, and individuals and non-profit companies might even be discouraged from participating in renewable energy. Environmental tax, subsidies, cheap fossil fuels, and low tariffs could be disincentives. Furthermore, land use is another challenge to the low-carbon energy transition as, for instance, solar farms have changed land-use dynamics, provoking some residents to resist land-use change. As a result, human rights to the landscapes might be breached, enabling citizens to ask for compensation [7].

Transition governance may be defined as a multi-faceted, multi-actor, multi-level, and multi-phase governing process that enables systemic transitions of socio-technical systems toward sustainability. Therefore, gradual reformation is needed, especially in authoritarian countries, while they generally continue to adhere to the established command-and-control rule, causing conflicts in transitioning to low-carbon energy systems [8]. The low-carbon energy transition requires the universal adoption of innovative technologies and regulations adjustments, such as regulatory standards or carbon pricing regimes, or even fewer regulations could improve the efficiency of the low-carbon energy transition [9]. Besides changing customer behavior and policy reformation, the energy transition needs a fundamental change in infrastructure. According to the challenges mentioned above, the low-carbon energy transition has faced many social, economic, environmental, technical, and institutional challenges, motivating the present study to figure out what these challenges are and how The EU has dealt with these challenges.

To this end, an integrated Multicriteria Decision Making (MCDM) method under Fermatean fuzzy sets (FFSs) is applied to determine the importance of the identified challenges and evaluate the performance of the EU in dealing with the challenges. Stepwise Weight Assessment Ratio Analysis (SWARA) is applied to determine the subjective weight of challenges, and MEthod based on the Removal Effects of Criteria (MEREC) is applied to determine the objective weight of indicators. After calculating weights, the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) is applied to rank the EU countries based on their performance in dealing with the weighted challenges. Also, FFSs are applied to deal with uncertainties in decision-making, making the proposed method more reliable.

The structure of the present study is presented as follows: Sect. 2 presents the challenges of the low-carbon energy transition. The method and materials are presented in Sect. 3. Results are presented in tables and charts and discussed in Sect. 4. Section 5 presents a sensitivity analysis. Finally, broad conclusions and policy implementations are presented in Sect. 6.

2 Challenges of the low-carbon energy transition

The present study reviewed the literature to identify challenges from 2013 to 2023. Table 1 shows the identified challenges and their related indicators. In order to develop Table 1, a new technique called PSALSAR was used with six main steps: Protocol, Search, AppraisaL, Synthesis, Analysis, and Report [3], presented below:

- Step 1: Research protocol. Ensuring transparency, reproducibility, and a systematic approach in evaluating literature is crucial to reducing subjectivity in any study. At this stage, it is essential to define the scope of the current research, develop research questions, and determine the most appro-

Table 1 Challenges and indicators found through a systematic literature review are categorized into four challenges, seventeen sub-challenges, and fifty-three indicators

Challenge	Sub-challenge	Indicator
Social (C_1)	Public engagement (SC_1)	Share of zero-emission vehicles in newly registered passenger cars-% (I_1) GHG emissions per capita- kg CO_2eq person^{-1} (I_2) GHG intensity of power & heat generation- t CO_2eq MillionEUR^{-1} (I_3) Average CO_2 emissions of new passenger cars- g CO_2 km^{-1} (I_4)
	Public awareness (SC_2)	The general advancement of knowledge: R&D financed from General University Funds (GUF)- Million Euro (I_5) The general advancement of knowledge: R&D financed from other sources than GUF- Million Euro (I_6)
	Public resistance (SC_3)	Share of renewable energy in gross final energy consumption-% (I_7) Renewable energy share in transport (RES-T)-% (I_8) Renewable electricity share (RES-E)-% (I_9) Renewable energy for heating & cooling (RES-H&C)-% (I_{10}) Fossil fuel avoidance by renewable energy-% (I_{11})
	Energy justice (SC_4)	Energy affordability-% (I_{12}) Harmonised Index of Consumer prices-% (I_{13}) Inability to keep home adequately warm-% (I_{14}) Household electricity prices- EUR kWh^{-1} (I_{15}) Household gas prices- EUR kWh^{-1} (I_{16})
	Labor transition (SC_5)	Total employment in renewables- employed persons (1000) (I_{17})
	Energy security (SC_6)	Aggregate supplier concentration index (from extra-EEA suppliers)- (0–1000) (I_{18}) Net import dependency-% (I_{19}) N-1 rule for gas infrastructure-% (I_{20}) Electricity interconnection-% (I_{21}) Market concentration index - power generation- (0–10,000) (I_{22}) Market concentration index - wholesale gas supply- (0–10,000) (I_{23}) Available energy, energy supply, and final energy consumption per capita- Kilograms of oil equivalent (KGOE) per capita (I_{24})
Economic (C_2)	Investment (SC_7)	Companies producing at least 5% of the net electricity generation- Number (I_{25}) Companies with at least 5% of the electricity generation-% (I_{26}) Companies with at least 5% of the electricity capacity-% (I_{27}) Electricity retailers- Number (I_{28}) Gross domestic product at market prices- Million Euro (I_{29})
	Mitigation and adaptation costs (SC_8)	GHG avoided emissions due to renewable energy-% vs. 2005 (2005 = 0.0%) (I_{30}) GHG emissions reductions (the base year 1990)-(0–100) (I_{31}) GHG Intensity of Energy [kg CO_2 eq. toe^{-1}] (I_{32}) GHG intensity of the economy- t CO_2eq MillionEUR^{-1} (I_{33}) Energy productivity- Euro per kilogram of oil equivalent (KGOE) (I_{34})
	Subsidies (SC_9)	Fossil Fuel Subsidies- USD (I_{35}) Total environmental taxes USD (I_{36})
Environmental (C_3)	Land use (SC_{10})	Land Use- Square kilometer (I_{37}) Land cover- Square kilometer (I_{38})
	Pollutions (SC_{11})	Landfill rate of waste excluding major mineral wastes-% (I_{39})
	Resource consumption (SC_{12})	Raw material consumption (RMC)- Thousand tonnes (I_{40})
Institutional and technical (C_4)	Short-termism (SC_{13})	Imports of electricity and derived heat by partner country- Gigawatt-hour (I_{41}) Imports of natural gas by partner country- Million cubic meters (I_{42}) Imports of oil and petroleum products by partner country Million cubic meters (I_{43}) Imports of solid fossil fuels by partner country Million cubic meters (I_{44})
	Innovative policies (SC_{14})	Patent on ENV technologies- Patents per million habitants (I_{45}) Patents on Energy Union priorities- Patents per million habitants (I_{46})
	Reformations (SC_{15})	Environmental policies- Number (I_{47})
	Lack of standards (SC_{16})	Total government budget allocations for R&D- Million Euro (I_{48})
	Lack of infrastructure (SC_{17})	Transport, telecommunication, and other infrastructures- Million Euro (I_{49}) New electricity capacity connected- Megawatt (I_{50}) Gross electricity production-Hydro- Gigawatt-hour (I_{51}) Gross electricity production-Wind- Gigawatt-hour (I_{52}) Gross electricity production - Gigawatt-hour (I_{53})

priate strategies to achieve the study's objective. The primary research, which the systematic review addressed, is: What impediments and obstacles are encountered in implementing the low-carbon energy transition?

- Step 2: Searching. Developing and executing an effective search strategy is crucial. Choosing a suitable database is imperative to ensure high-quality literature and a comprehensive coverage of available papers. Consequently, the following research strings were utilized to retrieve all articles indexed on Scopus and Web of Science:

Scopus: TITLE-ABS-KEY (("low carbon energy transition") OR ("low carbon transition") OR ("green energy transition") OR ("just energy transition") OR ("renewables" AND "energy transition")) OR ("challenge" AND "renewable" AND "energy transition"))
WOS: All = ((low carbon energy transition) OR (low carbon transition) OR (just energy transition) OR (green energy transition) OR (renewables AND energy transition) OR (renewables AND energy transition) OR (challenge AND renewable AND energy transition)).

- Step 3. Appraisal. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol has been used to select articles that meet the search criteria by the current research objectives. Only publications that satisfy the search criteria have been chosen. To be included, the articles must meet two criteria: firstly, the search keywords must appear in the title, abstract, or keywords, and secondly, the articles must have been published in a peer-reviewed scientific journal. Also, the following requirements apply to exclusion: review papers, editorial letters, chapter books, conference proceedings, academic theses, non-English language studies, and duplicated publications.
- Step 4. Synthesis. The collected data has been split into two categories: general and specific. General information includes the year of publication, journals, case study location, and future directions. On the other hand, specific information covers research gaps, objectives, and outcomes.
- Step 5. Analysis. This step's primary focus is finding solutions to the fundamental research questions and examining the classified information related to the research needs.
- Step 6. Report. This step involves highlighting the critical aspects of step 5. The literature review findings are summarized in the 27-point checklist of the PRISMA statement. The following results of the systematic review are presented in detail.

2.1 Social challenges

2.1.1 Public engagement

Most research has disregarded the critical role of public engagement in low-carbon energy transition as they take only technical issues into account. Networks of public and private stakeholders could foster interactions between organizations. As a result, knowledge could be effectively transferred, enhancing the stakeholders' engagement [10]. Also, public acceptance is a severe challenge, impacting strategy development; however, public acceptance and business support could facilitate the low-carbon energy transition. Socio-cultural settings affect public acceptability in different countries, requiring the low-carbon energy transition to include social issues as it is vital for a successful and equitable energy transition [11].

2.1.2 Public awareness

Small businesses, cities, and governments must adopt the low-carbon energy transition, requiring public education and awareness. Emerging interests might increase public awareness, encouraging enterprises and policymakers to use low-carbon energies. In contrast, inadequate training and, in general, weak public awareness are severe barriers to adopting renewable energies [12]. Effective public education could succeed more in open and transparent communities involving social networks, diverse professionals, and policymakers. Also, stakeholders could disagree on low-carbon energy transition and decarbonization, encouraging policymakers to improve public education to raise public awareness [13]. As a result, knowledge dissemination encourages behavior changes by increasing public awareness; thus, the community's increasing public contribution toward sustainability could be seen [14].

2.1.3 Public resistance

The low-carbon energy transition could affect the revenue of companies active in energy sectors now, and it could be exacerbated by a lack of supporting policies for adopting new technologies. In general, regime change is required in the low-carbon energy transition path through changes in production processes, infrastructure and institutions, and customer behavior. Uncertainties associated with regime change, magnitude, and duration significantly affect public resistance to changes [15]. As a result, the fundamental changes regarding the low-carbon energy transition might require decades of policy development since social structures are eventually rebuilt toward a low-carbon system. Also, resistance to change could be caused by public debates around how the low-carbon energy transition negatively impacts society [16].

2.1.4 Energy justice

An energy system where all stakeholders could equitably take advantage of benefits could bring justice to its stakeholders. Justice has four types: (1) procedural justice means participating in decision-making promoting equity; (2) distributional justice means balancing environmental pros and cons and related obligations; (3) justice recognition refers to fully guaranteed equal rights; and (4) justice cosmopolitan means all stakeholders deserve just energy as they are equal. On top of that, energy justice is a niche for boosting innovative alternatives and promoting democratic energy systems [17]. Just energy transition considers social justice as a core to the energy transition, and its goal is to hinder social inequalities or exacerbate existing ones. Less public engagement might result in less responsive and representative policy-making, which causes hatred, inequality, and tension in society. Also, labor unions and governments agreed to reduce coal usage, facilitating a low-carbon energy transition. As a result, those working in coal mines could be re-skilled and work in a low-carbon energy system, though some might lose their jobs permanently [17].

2.1.5 Labor transition

The low-carbon energy transition may create job positions in green industries; however, the overall effect on the labor market relies on the likelihood of workers quitting non-green sectors. Even if all new green job positions were filled exclusively by staff who leave neutral industries, the net transition's inflationary effect would be a mixture of job creation in green industries, job loss in neutral industries, and job loss in non-green industries [18]. On top of that, there might be some barriers to labor transition due to skill mismatches or shortages and demographical issues that require labor relocating. As a result, it is vital to determine whether renewables require a workforce to deliver the same energy level as fossil fuels by providing job positions such as operation and maintenance, equipment production, installation, and supply [19].

2.1.6 Energy security

It could be defined as the efficiency of the energy mix provided through international and domestic resources, energy dependency, and investment flexibility to fulfill energy needs. A significant challenge is moving toward the low-carbon energy transition without undermining energy justice and security [20]. Energy security could also be provided by (1) reviewing all available energy alternatives, suppliers, and services; (2) reducing energy demand through improving efficiency; (3) replacing non-efficient energy suppliers, infrastructures, and technologies; and (4) restricting new energy demands for fossil fuels [21]. Achieving a sustainable and secure energy system is challenging as it requires innovative technologies, an empowered economy, and managing energy demand and supply [22].

2.2 Economic challenges

2.2.1 Investment

More investment in the low-carbon energy transition is required as a significant imbalance exists between current and required investments. Off-grid renewables also are relatively cost-effective for delivering energy to rural areas; however, significant investment is needed. On top of that, adopting renewables could decrease gross domestic production or labor productivity, but the intensity and duration depend on required investments [23]. Governments should also provide adequate incentives to cope with public resistance. Furthermore, another government's contribution could be providing commercial incentives to decrease investment risks in public money investment. A lack of special financial incentives could be a significant risk in transitioning to a low-carbon energy system [24]. Local and global investments are required to deal with challenges to the low-carbon energy transition, and individuals and non-profit companies might even be discouraged from participating in renewable energy. Environmental tax, subsidies, cheap fossil fuels, and low tariffs could be disincentives. Significant efforts should encourage private sectors to invest in renewable energy technologies to alleviate perceived risks and uncertainties associated with the low-carbon energy transition [25].

2.2.2 Mitigation and adaptation costs

Mitigation costs are expenses associated with meeting climate change goals, and adaptation costs are expenses associated with making people resilient. A cost-effective and reliable path to a low-carbon energy system should be designed to prevent the adverse effects of global warming. The transition costs also comprise construction, operation, maintenance, and social costs caused by carbon emissions [26]. The low-carbon transition costs are enormous owing to the complexity of energy systems, stemming from various technologies, spatial-temporal elements, carriers, and high-investment infrastructure. Thus, cost reduction is beneficial but challenging since numerous transition paths associated with various transition policies, schedules, and speed would cause significant differences in transition costs despite similar transition goals [23].

2.2.3 Subsidies

Fossil fuel subsidies given by governments hinder moving toward the low-carbon energy system, requiring governments to phase out subsidies to GHG emissions by minimizing energy consumption. It is believed that fossil fuel subsidies increase energy consumption excessively; thus, reducing subsidies would reduce CO_2 emissions. Recently, removing fossil fuel subsidies has benefited significantly due to reduced oil prices and decreased energy consumption [27]. Additionally, governments should advance market-based energy trade and hinder a resurgence of fossil fuel subsidies. Governments have a monopoly on setting energy prices via subsidies. Thus, the market price for energy might be affected, impeding the low-carbon energy transition [28].

2.3 Environmental challenges

2.3.1 Land use

Land acquisition is vital for moving toward a low-carbon energy system as it is needed to build, for instance, solar farms, affecting the land-use patterns worldwide, and it is considered a distinguishing aspect of the global land rush. The required lands for building farms should be appropriate in size and geographical placement; however, these lands are rare despite adequate investments [29]. As a result, land grabs could have happened, as many of these lands are not public properties; that is why only the lands meet the requirements where they are governmental. Land grabbing refers to enclosing enormous lands, frequently forced by capitalism or extra-economic pressure. Also, land grabbing sometimes happens under sustainable development goals, called green grabbing [30]. Land scarcity is another challenge to the low-carbon energy transition associated with the increasing competition between land-use priorities.

2.3.2 Pollutions

Waste and pollution management, especially for nuclear energy, is challenging as people are concerned about radioactive waste. Also, biofuels could emit pollution, such as particulate matter, CO_2, hydrocarbons, sulfur dioxide, and nitrogen oxides; on the other hand, plants that are used for biomass could reduce harmful gases through photosynthesis [31]. Also, one of the most common ways to deal with waste and pollution is by landfilling; however, leachate formation is the leading risk connected to landfilling, which often happens illegally. Harmful substances for the environment are created due to chemical deterioration processes, rain seeping through garbage, and numerous harmful biological phenomena, including a mixture of obnoxious odors and gases and adverse effects on groundwater and soil, which are significant components of landfill emissions [32].

2.3.3 Resources consumption

Raw material consumption is another barrier to the low-carbon energy transition since statistics show a shortage of raw materials, such as lithium, cobalt, and copper. For instance, the global demand for copper has increased, exceeding the current copper production capacity. As a result, recycling industries or demand control should be considered not to jeopardize energy production [33]. Also, Adopting energy-efficient lighting facilities has increased the demand for various critical raw materials, including indium, germanium, and gallium. Also, aluminum, nickel, cobalt, and steel are widely used to generate solar panels. Thus, the demand for these materials would likely remain high over the following decades, disregarding the energy mix. Also, raw materials, such as sand, should be used for low-carbon buildings [34].

2.4 Institutional challenges

2.4.1 Short-termism

The governments ratify short-term policies to save countries politically and economically for a short period; however, they may hinder the transition to the low-carbon energy system or at least reduce its pace. Short-term revenue in petrostates like Kuwait, Iran, and Iraq is vital for political positions due to the high budgetary breakeven points, even if these countries lose their chance to have a sustainable energy system [35]. As a result, short-termism has become a part of policy-making, affecting long-term objects with short-term decisions; thus, it is required that governments contribute to energy transition by following long-term goals, not only just delivering short-term benefits [10].

2.4.2 Innovative policies

Innovative policies are generally required to move successfully toward a low-carbon energy system; however, high compatibility and flexibility for reconfiguration and changes are prerequisites for developing policies characterized by innovation and novelty [36]. As a result, authorities should acknowledge innovative policies regarding subsidies, standards, regulations, and information flow to remove barriers to low-carbon energy transition and spur innovation. In other words, authorities should take into account innovative measures to promote green and low-carbon technologies; thus, policies should be coordinated to follow low-carbon energy transition goals [11].

2.4.3 Reformations

Conflicts would be observed during all stages of the energy transition, including political conflicts, such as minimum tariffs, directly affecting financial returns. As a result, authorities should reform their process and laws to deal with conflicts, and their tasks in the transition should be developing new processes and coordination, providing required materials, setting regulations, and management [37]. On top of that, policy development, macroeconomy, and public awareness are interconnected, meaning that policy reformation may raise public awareness, and subsequently, customer behavior and the economy will be affected. Therefore, the flexibility and compatibility of policies should be determined to remove barriers to policy reformation when reformation might affect the critical aspects of the policy mix regarding energy transition [38].

2.4.4 Lack of standards

A set of explicit standards and regulations leads the energy supply toward a predetermined path. It is believed that the lack of explicit standards is a severe challenge to the low-carbon energy transition, and regulatory frameworks are underdeveloped, reducing the pace of energy transition due to increasing uncertainties and vagueness in the processes, including distributing information regarding the low-carbon technologies [39]. Solid and explicit regulations that include all influencing operations are vital to deal with all misunderstandings, especially regarding toxic pollution. For instance, most regulations have been developed to reduce GHG emissions; however, companies can still produce pollution in other forms, such as groundwater pollution [40]; thus, explicit environmental guidelines are required.

2.4.5 Lack of infrastructure

Increasing demand for renewable energy threatens the current grid's stability since innovative energy infrastructures are required for the energy transition; however, a lack of infrastructure could reduce the pace of the energy transition [24]. The privatization of infrastructure has shrunk the public capacity to develop required energy infrastructures, affecting the climate change mitigation activities by governments; thus, it is required that both private and public sectors collaborate to overcome barriers connected to energy infrastructures [10]. Also, Kuamoah [41] mentioned that another barrier to renewable energy adoption is a lack of infrastructure and undeveloped and aged energy grids. Nevertheless, decisions about which renewable energy is needed and where to develop would result in inequality in energy and economic development, entailing energy poverty at the household level. Asset and infrastructure privatization and budget constraints have significant adverse effects on the capacity of public sectors to deal with climate change mitigation issues. As a result, infrastructure investment is vital since overall transition costs will increase immediately due to deploying large-scale renewables and phasing out fossil energy. Overall system costs encompass production, import, export, conversion, infrastructure, and energy storage [42].

3 Materials and methods

As mentioned in the introduction, the present study applied an integrated method under FFSs to evaluate the performance of the EU countries in dealing with the challenges of the low-carbon energy transition. To this end, 53 indicators, see Table 1, were determined to measure the performance of countries in dealing with 17 challenges. Afterward, FF-SWARA is applied to determine the importance of the identified challenges. For this purpose, the present study has asked ten experts through an online survey to support challenges using the linguistic variables shown in Table S1 of Supplementary Materials. Five experts were academics, and the minimum requirements for all experts were holding a master's degree in economics or related topics and having at least five years of experience in the energy sector. The number of experts should ideally range between 5 and 10. It is worth keeping in mind that surpassing the upper limit of 10 can result in considerable inconsistencies in the responses, undermining the data's reliability. Hence, it is prudent to adhere to this recommended range to guarantee the precision and consistency of the collected data.

Furthermore, Insights from Saaty [43], the creator of the Analytic Hierarchy Process, shed light on the number of experts required for effective MCDM methods. While Saaty did not recommend a specific number of experts, he stressed the significance of involving a small group of 3 to 7 experts to ensure a streamlined and productive decision-making process. This group size allows for seamless expert communication and collaboration [43]. A small group of 3 to 10 experts would be enough to apply MCDM methods. After calculating the subjective weights of challenges using FF-SWARA, the MEREC method was applied to calculate the objective weight of indicators. Finally, The TOPSIS method is applied to rank the EU countries for 2015 and 2020 based on their performance in dealing with the weighted challenges. The steps of the integrated method are explained in the following.

The integration of SWARA-TOPSIS or MEREC-TOPSIS was used to evaluate performance in different fields. For instance, Dincer et al. [44] recently applied an integrated SWARA-TOPSIS method under q-Rung Orthopair fuzzy soft sets to evaluate the performance of investigating alternatives in microgeneration energy technologies. Also, Patel et al. [45] used an entropy measure SWARA-TOPSIS method to assess the performance of waste management strategies under intuitionistic fuzzy sets, and Kamali Saraji et al. [46] used an integrated SWARA-TOPSIS method under Pythagorean fuzzy set to evaluate the performance of the EU countries in progressing toward sustainable energy development. Furthermore, Yadav et al. [47] used an improved

MEREC-TOPSIS to evaluate the performance of a 5G heterogeneous network for the Internet of Things under conventional fuzzy sets. Also, Nguyen et al. [48] used the integration of several multicriteria methods, including TOPSIS and MEREC, to evaluate the performance of powder-mixed electrical discharge machining of cylindrically shaped parts in 90CrSi tool steel, and Trung and Thinh [49] conducted comparative analyses using multicriteria methods, including TOPSIS and MEREC, to evaluate the performance of cutting machines under conventional fuzzy sets. According to recent literature, SWARA-TOPSIS and MEREC-TOPSIS were used in different fields for various purposes; however, the present study integrates them under a novel fuzzy extortion called FFSs to deal with a multi-layer and multicriteria performance evaluation problem to increase the accuracy and reliability of the obtained results by reducing the impact of subjectivity in the evaluation process.

On the other hand, the present study did not use a verification method such as the Delphi method due to the following reasons:

1. The main problem with verification approaches like the Delphi method is subjectivity, which lies in the lack of clear parameters for consensus [50]. Consequently, subjectivity might exclude some factors impacting the research dimensions due to the experts' biases and uncertainty. The method may not always provide a comprehensive understanding of a problem or issue, as it relies on the knowledge and expertise of the participating experts. It may overlook critical factors or perspectives [51]. However, as explained above, the present study aimed to develop a comprehensive framework of challenges, motivating the research to conduct a systematic review.
2. Although identified challenges were globally discussed, it should be noted that EU authorities measure all identified challenges and their related indicators. In other words, all the identified challenges are considered influential and essential enough to be measured and studied. As a result, data availability is a rigid reason not to exclude any challenges or related indicators.
3. The present study applied the SWARA method to determine the importance of challenges by ranking them [52]. The main advantage of SWARA over the Delphi method is that subjectivity never excludes a challenge; even experts might be biased [53]. In other words, a challenge might be considered less important than it is; however, it would never be excluded from the decision-making process, while the Delphi technique would exclude some challenges as the Delphi method refines challenges, but SWARA ranks them [54]. Therefore, SWARA has the potential to verify the identified challenges according to experts without excluding them, but with different importance.

Furthermore, the proposed method is used under FFSs, offering several advantages in handling uncertainty and decision-making, making them a valuable mathematical concept. FFSs provide a more flexible and generalized model for representing uncertainty than other fuzzy set theories, such as intuitionistic fuzzy sets. They can effectively capture a broader range of uncertainty scenarios in decision-making processes [55]. Also, FFSs facilitate efficient decision-making when uncertainty is crucial. Their ability to efficiently handle uncertain information makes them a powerful tool in multicriteria group decision-making processes, simplifying the description of expert inference [56]. On the other hand, researchers have developed extensions and applications of FFSs in various domains, including multicriteria decision-making methods like Simple Additive Weighting, Additive Ratio Assessment, and Viekriterijumsko Kompromisno Rangiranje. The literature demonstrates their adaptability and utility in real-world problem-solving [57, 58].

3.1 Preliminaries

Definition 1. [59]. A FFS is shown by Eq. (1) if is assumed to be a limited universe of discourse.

$$\mathrm{F} = \left\{ \langle f_i, (\alpha_F(f_i), \beta_F(f_i)) \rangle \middle| f_i \in \mathring{\mathrm{A}} \right\} \tag{1}$$

$\alpha_F, \beta_F : \mathring{\mathrm{A}} \to [0.1]$ are the belonging and non-belonging of $f_i \in \mathring{\mathrm{A}}$ in an FFS; subject to $0 \leq (\alpha_F(f_i))^3 + (\beta_F(f_i))^3 \leq 1$ for each $f_i \in \mathring{\mathrm{A}}$.

Definition 2. Equation (2) determines the indeterminacy degree (γ_ζ); if $\zeta = (\alpha_\zeta, \beta_\zeta) | \alpha_F, \beta_F \in [0, 1]$, $0 \leq {\alpha_\zeta}^3 + {\beta_\zeta}^3 \leq 1$.

$$\gamma_\zeta = \sqrt[3]{1 - {\alpha_\zeta}^3 - {\beta_\zeta}^3} \tag{2}$$

Definition 3. Equations (3) and (4) determine the score and accuracy functions of γ.

$$h(\gamma) = {\alpha_\zeta}^3 - {\beta_\zeta}^3 | 1 \leq h(\gamma) \leq 1 \tag{3}$$

$$\hbar(\gamma) = {\alpha_\zeta}^3 + {\beta_\zeta}^3 | 0 \leq \hbar(\gamma) \leq 1 \tag{4}$$

Definition 4. Some basic operators of FFSs are presented by Eqs. (5)–(10); Let $\zeta = (\alpha_\zeta, \beta_\zeta), \zeta_1 = (\alpha_{\zeta_1}, \beta_{\zeta_1})$ and $\zeta_2 = (\alpha_{\zeta_2}, \beta_{\zeta_2})$.

$$\zeta_1 \bigcap \zeta_2 = \left(min\{\alpha_{\zeta_1}, \alpha_{\zeta_2}\}, max\{\beta_{\zeta_1}, \beta_{\zeta_2}\}\right) \tag{5}$$

$$\zeta_1 \bigcup \zeta_2 = \left(max\{\alpha_{\zeta_1}, \alpha_{\zeta_2}\}, min\{\beta_{\zeta_1}, \beta_{\zeta_2}\}\right) \tag{6}$$

$$\zeta_1 \oplus \zeta_2 = \left(\sqrt[3]{\alpha_{\zeta_1}^3 + \alpha_{\zeta_2}^3 - \alpha_{\zeta_1}^3 \alpha_{\zeta_2}^3}, \beta_{\zeta_1}\beta_{\zeta_2}\right) \tag{7}$$

$$\zeta_1 \otimes \zeta_2 = \left(\alpha_{\zeta_1}\alpha_{\zeta_2}, \sqrt[3]{\beta_{\zeta_1}^3 + \beta_{\zeta_2}^3 - \beta_{\zeta_1}^3 \beta_{\zeta_2}^3}\right) \tag{8}$$

$$\updownarrow\zeta = \left(\sqrt[3]{1 - \left(1 - \alpha_\zeta^3\right)^{\updownarrow}}, (\beta_\zeta)^{\updownarrow}\right), \updownarrow > 0 \tag{9}$$

$$\zeta^{\updownarrow} = \left((\alpha_\zeta)^{\updownarrow}, \sqrt[3]{1 - \left(1 - \beta_\zeta^3\right)^{\updownarrow}}\right), \updownarrow > 0 \tag{10}$$

3.2 Integrated FF-SWARA-MEREC-TOPSIS

3.2.1 Calculating subjective weights of challenges

Step 1 Decision matrix construction

$\mathbb{N}$ is the decision matrix and is represented by $\mathbb{N} = (d_{ik}), \forall i = 1, \ldots, m; k = 1, \ldots, l;$ where d_{ik} presents the given value to challenge (i) by k^{th} decision experts. A set of challenges is represented by $\{c_1, c_2, \ldots, c_m\}$, and a group of decision experts represented by $\{e_1, e_2, \ldots, e_l\}$.

Step 2 Aggregating

Experts supported challenges individually; thus, individual supports must be aggregated using the Fermatean fuzzy weighted averaging operator by Eq. (11). Let $A = (a_i)_m$ be the aggregated FF-decision matrix, and ω_k is the importance of experts.

$$a_i = \left(\sqrt[3]{1 - \prod_{k=1}^{l}\left(1 - (\alpha_{ik})^3\right)^{\omega_k}}, \prod_{k=1}^{l}(\beta_{ik})^{\omega_k}\right) \tag{11}$$

Step 3 SWARA steps

Step 3.1 Eq. (12) calculates the score function.

$$\acute{S} = \frac{\alpha_\zeta + \beta_\zeta - \gamma_\zeta + 1}{2} \tag{12}$$

Step 3.2 According to decision experts' preferences, challenges are ordered from the most to the least important.
Step 3.3 importance of each challenge is compared with the best challenge, (Δ_i) is their difference.
Step 3.4 The comparative coefficient Λ_i is determined by Eq. (13). The difference between i and $i - 1$ shows the successive comparative importance.

$$\Lambda_i = \begin{cases} 1 i = 1 \\ \acute{s}_i + 1 i > 1 \end{cases} \tag{13}$$

Step 3.5 The challenge's importance ϕ_i is determined by Eq. 14.

$$\phi_i = \begin{cases} 1 i = 1 \\ \frac{\phi_{i-1}}{\Lambda_i} i > 1 \end{cases} \tag{14}$$

Step 3.6 Eq. (15) calculates the final subjective weights.

$$w_i = \frac{\phi_i}{\sum_{i=1}^{n}\phi_i} \tag{15}$$

3.2.2 Calculating objective weights of challenges

Step 1 Score matrix

Let $\Xi = (z_{tj})_{t \times j}, \forall t = 1, \ldots, y; j = 1, \ldots, n;$ a score matrix of sub-challenges created by Eq. (16). A set of sub-challenges is represented by $\{sc_1, sc_2, \ldots, sc_n\}$, and a set of countries is represented by $\{A_1, A_2, \ldots, A_y\}$.

$$\Xi = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{y1} & \ldots & z_{yn} \end{bmatrix} \tag{16}$$

Step 2 Normalization

Let $\bar{\Xi} = \left(\bar{z}_{tj}\right)_{t\times j}$ the normalized score matrix created by Eq. (17).

$$\bar{z}_{tj} = \begin{cases} \frac{\min\limits_j z_j}{z_{tj}}, j \in N_b \\ \frac{z_{tj}}{\max\limits_j z_j}, j \in N_n \end{cases} \tag{17}$$

Step 3 MEREC steps

Step 3.1 Calculating the overall performance

Equation (18) calculates the overall performance of the alternatives.

$$\Psi_t = \ln\left(1 + \left(\frac{1}{n}\sum_j \left|\ln\left(\bar{z}_{tj}\right)\right|\right)\right) \tag{18}$$

Step 3.2 Calculating the overall performance of alternatives by removing each criterion

Let σ_{tj} be the overall performance of i_{th} alternative according to the removal of j_{th} challenge. Equation (19) calculates σ_{tj}:

$$\sigma_{tj} = \ln\left(1 + \left(\frac{1}{n}\sum_{g,g\neq j} \left|\ln\left(\bar{z}_{tj}\right)\right|\right)\right) \tag{19}$$

Step 3.3 Absolute deviations

Equation (20) determines the values of σ_{tj}:

$$\sigma_{tj} = \sum_j \left|\sigma_{tj} - \Psi_t\right| \tag{20}$$

Step 3.4 Final objective weights

Equation (21) calculates the objective weights (w_t):

$$w_t^o = \frac{\sigma_{tj}}{\sum_j \sigma_{tj}} \tag{21}$$

3.2.3 Ranking alternatives (countries)

Step 1 Score matrix

This step is similar to step 1 in calculating the objective weights.

Step 2 Normalization

Let $\hat{\Xi} = \left(\hat{z}_{tj}\right)_{t\times j}$ the normalized score matrix created by Eq. (22).

$$\hat{z}_{tj} = \frac{z_{tj}}{\sqrt{\sum_{t=1}^{y} z_{tj}^2}} for\ (j = 1,\ldots,n) \tag{22}$$

Step 3 Weighted matrix (TOPSIS steps)

After calculating the objective and subjective weights using MEREC and SWARA, the weighted decision matrix should be structured by Eq. (23), where w_q^p is pilars' weights.

$$\upsilon_{tj} = \hat{z}_{tj} * w_t^o * w_i^s * w_q^p (q = 1,\ldots,h) \tag{23}$$

Step 3.1 Positive and negative ideal solutions

The positive and negative ideal solutions are determined by Eqs. (24) and (25).

$$A^+ = \left\{\left(\max_t \upsilon_{tj} | j \in J\right), \left(\min_t \upsilon_{tj} | j \in J'\right) | i = 1,\ldots,m\right\} = \left\{\nu_1^+, \nu_2^+, \ldots, \nu_n^+\right\} \tag{24}$$

$$A^- = \left\{\left(\min_t \upsilon_{tj} | j \in J\right), \left(\max_t \upsilon_{tj} | j \in J'\right) | i = 1,\ldots,m\right\} == \left\{\nu_1^-, \nu_2^-, \ldots, \nu_n^-\right\} \tag{25}$$

Where $J = \{j = 1,2,\ldots,n | j \text{ associated with the benefit criteria}\}$, and $J' = \{j = 1,2,\ldots,n | j \text{ associated with the cost criteria}\}$.

Step 3.2 The Separation Measure

The separation measure for each alternative is calculated using Eqs. (26) and (27).

$$S_t^+ = \sqrt{\sum_{j=1}^{n}\left(\upsilon_{tj} - \nu_j^+\right)^2} (t = 1,\ldots,y) \tag{26}$$

$$S_t^- = \sqrt{\sum_{j=1}^{n}\left(\upsilon_{tj} - \nu_j^-\right)^2} (t = 1,\ldots,y) \tag{27}$$

Step 3.3 Relative closeness

The relative closeness is calculated in this step using Eq. (28).

$$C_i^* = \frac{S_t^-}{S_t^- + S_t^+}, 0 < C_i^* < 1, t = 1, \ldots, y \quad (28)$$

Where $C_i^* = 1 \ if \ A_i = A^+$, and $C_i^* = 0 \ if \ A_i = A^-$.

Step 4 Ranking the alternatives

Finally, the alternatives can be ranked according to the descending order of C_i^*.

4 Results and discussion

The first step of the proposed framework is constructing the decision matrix. Tables S2 and S3 show the decision matrix for 2015 and 2020, respectively.

Afterward, the objective weights for indicators were calculated using the MEREC for both years. The results of MEREC for both years are shown in Table 2.

Subsequently, the subjective weights of sub-challenges were calculated using the SWARA. Table 3 shows the support given by experts in linguistic variables.

Subsequently, Table 4 shows the final subjective weights of sub-challenges.

According to Table 4, energy justice is the most significant social challenge to low-carbon energy adoption. Justice as a primary energy research problem has risen, particularly over the years; however, bringing justice to the energy sector would benefit the low-carbon energy transition. Energy justice could reduce risks within the energy sector by dealing with poor records of social, environmental, and institutional issues within the energy sector. Surprisingly, the energy sector has been inadequately evaluated and untreated in light of delivering justice for society, while it has caused many environmental and climate issues. Furthermore, a comprehensive framework is provided by energy justice, including (1) distributive justice, related to distributing benefits and costs of energy sectors between stakeholders justly; (2) procedural justice, focusing on whether legal processes have been justly followed; (3) restorative justice, focusing on rectifying any injustice connected to the energy sector; and (4) recognition justice, related to indigenous communities rights, and in general the recognition of rights between various groups [60].

Furthermore, mitigation and adaptation costs are the most influential economic challenge to the low-carbon energy transition. More significant mitigation can lessen the long-term requirement for adaptation, and more adaptation can reduce mitigation costs by enhancing coping and adaptive capacities; thus, mitigation

Table 2 Objective weights of fifty-three indicators, which are determined by the MEREC method, and all values are between zero and one

Sub-challenges	Indicators	2015	2020
SC1	I1	0.314	0.411
	I2	0.285	0.217
	I3	0.361	0.347
	I4	0.039	0.025
SC2	I5	0.661	0.732
	I6	0.339	0.268
SC3	I7	0.162	0.094
	I8	0.441	0.234
	I9	0.143	0.191
	I10	0.162	0.305
	I11	0.092	0.175
SC4	I12	0.208	0.192
	I13	0.156	0.158
	I14	0.348	0.349
	I15	0.163	0.179
	I16	0.125	0.123
SC5	I17	1.000	1.000
SC6	I18	0.116	0.099
	I19	0.125	0.128
	I20	0.231	0.370
	I21	0.168	0.116
	I22	0.136	0.093
	I23	0.096	0.093
	I24	0.128	0.101
SC7	I25	0.163	0.127
	I26	0.160	0.172
	I27	0.156	0.188
	I28	0.258	0.254
	I29	0.263	0.259
SC8	I30	0.198	0.141
	I31	0.209	0.223
	I32	0.211	0.227
	I33	0.187	0.203
	I34	0.195	0.205
SC9	I35	0.565	0.592
	I36	0.435	0.408
SC10	I37	0.415	0.371
	I38	0.585	0.629
SC11	I39	1.000	1.000
SC12	I40	1.000	1.000
SC13	I41	0.145	0.143
	I42	0.305	0.265
	I43	0.220	0.225
	I44	0.331	0.368
SC14	I45	0.166	0.284
	I46	0.834	0.716
SC15	I47	1.000	1.000
SC16	I48	1.000	1.000

Table 2 (continued)

Sub-challenges	Indicators	2015	2020
SC17	I49	0.179	0.200
	I50	0.206	0.129
	I51	0.201	0.234
	I52	0.154	0.284
	I53	0.260	0.153

and adaptation are not mutually independent. Climate change impacts are tangible, requiring necessary actions, such as mitigation through reducing both future and current GHG emissions and adaptation through adjusting to the impacts of climate change. To this end, a productive collaboration between governments, policymakers, and environmental organizations is required to develop policies for climate change mitigation and adaptation [61]. Stakeholder participation is also crucial for adopting an

Table 3 Experts' evaluations of sub-challenges, which are used for determining the subjective weights using the SWARA method

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14	SC15	SC16	SC17
E1	EH	EH	VH	VH	H	VH	H	H	H	M	M	M	M	M	M	H	VH
E2	VH	H	VH	EH	EH	EH	H	H	H	M	H	H	H	H	M	MH	EH
E3	H	H	EH	EH	VH	VH	VH	VH	VH	H	M	M	H	H	H	M	H
E4	MH	MH	MH	H	H	H	MH	MH	MH	M	M	MH	H	VH	M	M	H
E5	H	MH	H	VH	VH	VH	M	M	M	VH	VH	MH	M	M	M	H	H
E6	M	M	M	H	H	H	H	VH	H	EH	EH	EH	H	H	H	H	H
E7	VH	VH	EH	EH	MH	MH	M	M	M	H	H	H	H	MH	M	MH	MH
E8	M	MH	H	H	MH	VH	MH	MH	M	VH	MH	MH	MH	MH	MH	MH	MH
E9	H	H	VH	EH	M	VH	H	MH	M	M	M	M	ML	M	ML	M	H
E10	M	M	ML	MH	M	MH	H	H	ML	H	MH	ML	M	MH	M	MH	MH

Table 4 Different coefficients and final subjective weights of sub-challenges were determined by the SWARA

	Crisp Values	Comparative Significance of Criteria Value (s_j)	Coefficient (k_j)	Recalculated Weight (p_j)	Criteria Weight (w_j)
C1					
SC4	0.595	-	1.000	1.000	0.185
SC6	0.516	0.079	1.079	0.927	0.171
SC3	0.508	0.008	1.008	0.919	0.170
SC5	0.446	0.062	1.062	0.865	0.160
SC1	0.440	0.006	1.006	0.860	0.159
SC2	0.421	0.019	1.019	0.844	0.156
C2					
SC8	0.389	-	1.000	1.000	0.337
SC7	0.382	0.007	1.007	0.993	0.335
SC9	0.337	0.018	1.018	0.976	0.329
C3					
SC10	0.409	-	1.000	1.000	0.337
SC11	0.399	0.010	1.010	0.990	0.334
SC12	0.367	0.015	1.015	0.976	0.329
C4					
SC17	0.451	-	1.000	1.000	0.220
SC14	0.355	0.096	1.096	0.912	0.201
SC13	0.337	0.018	1.018	0.896	0.197
SC16	0.326	0.011	1.011	0.886	0.195
SC15	0.279	0.046	1.046	0.847	0.186

integrated governance approach that improves adaptation-mitigation co-benefits, while a lack of understanding of adaptation and mitigation may influence the level of public support required to undertake action plans [62].

Moreover, land use is the most significant environmental challenge to the low-carbon energy transition. The area used by renewable developments is changed, either directly or visually. Adopting renewables on a global scale is spatially broad since, for instance, establishing solar parks has enabled energy and land dispossessions [29]. Therefore, land use is extensively considered a spatial metric to measure the landscape impacts of renewable developments. Low-carbon energy transition pathways should urgently comprise the geophysical conditions and land availability. Fossil fuel energy systems use a negligible amount of land, whereas renewable energy sources can alter landscapes and ecosystems radically. Land use affects biodiversity, ecosystems, and geochemical cycles. It also affects society's well-being owing to its impact on recreation, noise, views, and quality of life [63]. A reliable assessment framework is required to design comprehensive transition policies and pathways to evaluate the impact of low-carbon transition on land use and its geographical contextualization in different scenarios [64].

Also, the lack of infrastructure is the most significant institutional and technical challenge to the low-carbon energy transition. The low-carbon energy transition could successfully happen through collaboration between local and international contributors with practical policies, modeling and optimization, technology, and infrastructure development and adaptation, such as smart grids [65]. In most developing nations, the absence of physical infrastructures for transmission and distribution networks and equipment and services required by power companies is a significant barrier to developing renewable energy. Most of this equipment is typically unavailable in these countries and is thus imported from industrialized nations. Since imported equipment is more expensive than locally produced equipment, generating renewable resources becomes prohibitively expensive in most countries. Limited equipment servicing and maintenance and a lack of technological dependability reduce customer satisfaction and impede low-carbon technology adoption. Subsequently, the EU's performance in dealing with the identified challenges to the low-carbon energy transition was evaluated for 2015 and 2020. Figure 1 shows the results.

According to Fig. 1, the most significant change belongs to Spain, as it improved its rank from 21st in 2015 to 11th in 2020, followed by Italy, which improved its rank from 19th in 2015 to 14th in 2020. However, the Netherlands ranked first in 2015 according to its performance in dealing with the identified challenges to the low-carbon energy transition in the present study, followed by Germany. Surprisingly, Germany ranked first in 2020, followed by the Netherlands, showing Germany has been trying to improve its performance over the years.

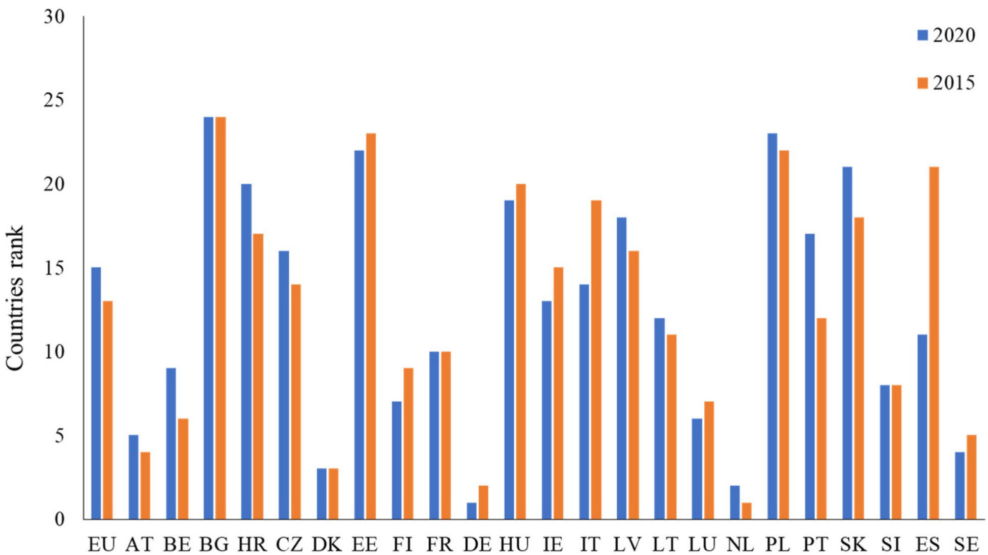

Fig. 1 Ranks of the EU countries according to their performances in dealing with the identified challenges of low-carbon energy transition

On top of that, the third place belongs to Denmark in both years, while other Nordic countries, such as Sweden and Finland, ranked fifth and ninth in 2015, respectively; and the same stats for these two countries in 2020 were fourth and seventh, showing their improvement in dealing with the identified challenges to the low-carbon energy transition. Furthermore, Baltic countries, including Estonia, Latvia, and Lithuania, ranked 23rd, 16th, and 11th in 2015. Estonia did not perform well among Baltic countries due to the high landfilling rate, adversely affecting the countries' rank. However, Estonia has improved its performance and ranked 22nd in 2020, while the performance of Latvia and Lithuania in 2020 weakened compared to 2015.

On the other hand, Bulgaria had the worst performance in the EU in both years. However, other countries in Eastern Europe have different records in these years. Visegrad countries, including Czech, Hungary, Poland, and Slovakia, ranked 14th, 17th, 22nd, and 18th in 2015. Surprisingly, the performance of all these countries weakened over the years, and they ranked 16th, 20th, 23rd, and 21st in 2020, respectively. However, the worst performance among Visegrad countries belongs to Poland in both years due to less developed infrastructure to meet the country's requirements for adopting low-carbon technologies. However, Slovenia, neighboring these countries, performs better than Visegrad countries, ranked 8th in both years.

Furthermore, central European countries performed differently than Germany, the best country in 2020. For instance, France was ranked 10th in both years, Luxembourg was ranked 7th and 6th in 2015 and 2020, and Austria was ranked 4th and 5th in 2015 and 2020. Also, Belgium, next to the Netherlands, the best country in 2015, was ranked 6th and 9th in 2015 and 2020, which is not enough improvement to deal with the identified challenges compared to other countries. Moreover, Italy, located in the south of Europe, improved its place from 19th in 2015 to 14th in 2020, and Ireland, located in the north of Europe, also improved its place from 15th in 2015 to 13th in 2020. Also, Portugal, next to Spain, has the weakest performance over five years and was ranked 12th and 17th in 2015 and 2020, respectively. However, according to Fig. 1, The EU still needs improvement in dealing with identified challenges to the low-carbon energy transition in the present study, as it was ranked 13th and 15th in 2015 and 2020 and weakened over five years. Figure 2 illustrates the changes over the five years.

According to Fig. 2, Spain has the most robust progress, and Portugal has the weakest over five years. Figure 3 illustrates the relative average growth for each challenge over the five years.

According to Fig. 3, Spain improved its rank by explicitly dealing with public resistance and increasing investments in low-carbon energy transition. Public resistance can influence policymakers and regulators. If there is strong public opposition to specific low-carbon energy projects or policies, it may lead to delays, changes in regulations, or even the abandonment of such initiatives. Conversely, public support can push policymakers to implement more ambitious and effective policies, and these results align with studies conducted by Huang [16], Baker and Phillips [66], and Urban and Nordensvard [67]. Also, any investment could boost moving toward a low-carbon energy system. For instance, the significance of investing in research and development to

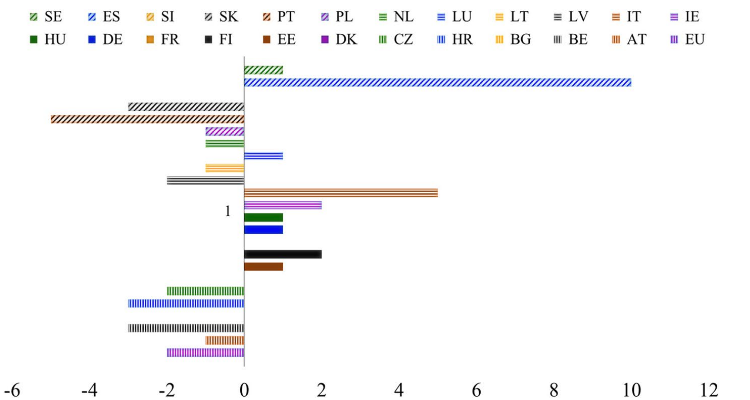

Fig. 2 Changes in the EU countries' ranks over the five years from 2015 to 2020- positive changes show growth in countries' ranks, while negative changes show the opposite, and zero means no change over the years

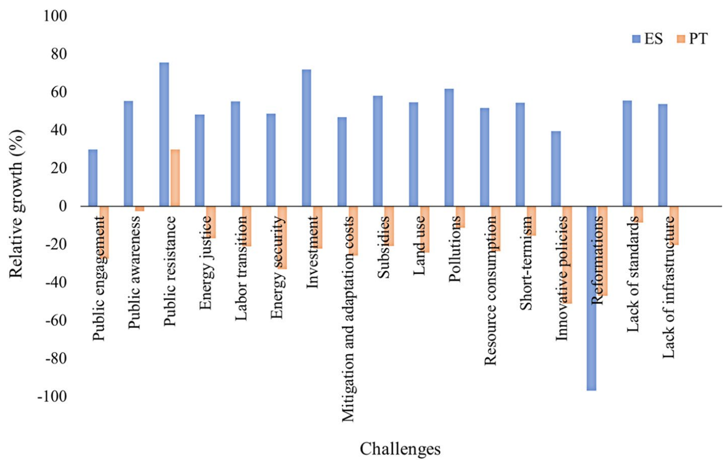

Fig. 3 Growth by focused challenges for Spain and Portugal, which had the highest and lowest relative growth over the five years from 2015 to 2020 in the EU

foster innovative low-carbon energy technologies cannot be overstated. Various entities such as governments, private companies, and philanthropic organizations often allocate funds to research novel renewable energy sources, energy storage solutions, and energy efficiency technologies. Also, implementing renewable energy infrastructure, encompassing solar farms, wind turbines, and hydropower facilities, is contingent on significant investment on a large scale. This investment is crucial for augmenting the proportion of renewable energy in the overall energy mix, and these results align with studies conducted by Mikulic and Kecek [68], Gelo et al. [69] and Chen et al. [70].

On the other hand, although Portugal focused on public resistance, the country failed to deal with other challenges adequately, especially in developing innovative policies. The inception of innovative policies often stems from the concerted efforts of governmental and international entities in outlining unequivocal and ambitious objectives aimed at mitigating carbon emissions and promoting the widespread adoption of low-carbon energy sources. These objectives collaboratively guide policymakers and business entities toward a shared mission; these results align with others [15, 36, 71]. Furthermore, according to the results, energy justice is the most influential challenge; however, Portugal could bring justice to its energy system compared to other countries. Energy justice emphasizes that everyone should have access to affordable and clean energy. As the transition to low-carbon energy sources progresses, it is important to ensure that vulnerable and low-income communities also benefit from these cleaner options rather than being left behind. The lack of significant progress in energy justice might impact progress in other fields, especially public engagement, and these results are in line with other investigators [72–74].

5 Sensitivity analysis

The utilization of sensitivity analysis is valuable in examining trade-offs between criteria. This approach enables decision-makers to understand better how changes in a specific criterion can impact the overall ranking of alternatives, thus empowering them to make more informed decisions. Additionally, sensitivity analysis provides scenario analysis, examining how different future conditions or scenarios may impact decision outcomes. The present studies assumed all four pillars of challenges impact equally on the low-carbon energy transition. However, the sensitivity of the proposed method is analyzed in this section under four scenarios so that in each scenario, one selected pillar would get the highest weight, and the rest would get the lowest weight. It should be noted that weights should be higher than zero and lower than one, and the sum of weights must equal one. This research's lowest assumed increment (weight) is 0.1, and the highest is 0.7. Figure 4 illustrates the results of the sensitivity analysis.

Figure 4 shows the sensitivity of the proposed method regarding radical changes in the importance of the challenge weights. Therefore, The proposed method can be applied under any assumptions. For instance, if environmental challenges were radically critical compared to

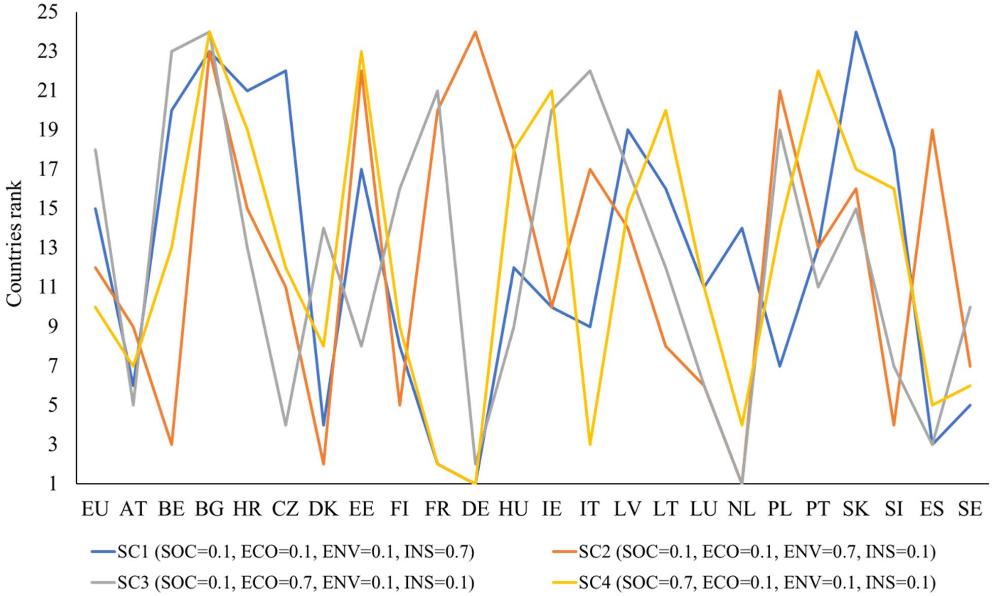

Fig. 4 Sensitivity analysis results under four scenarios for all the EU countries, showing how fluctuating ranks could be under various assumptions

other challenges, Germany would be one of the weakest countries, while in case of equal importance for challenges, Germany is the best country.

6 Conclusions

The present study identified challenges of the low-carbon transition through a literature review and, subsequently, identified indicators for evaluating the performance of the EU in dealing with the identified challenges. Afterward, an integrated MCDM framework under FFSs was developed to determine the subjective weight of identified challenges using Fermatean SWARA and determine the objective weight of indicators using MEREC, then evaluate the performance of the EU using TOPSIS according to weighted challenges and indicators. The results indicated that energy justice, mitigation, adaptation cost, land use, and lack of infrastructure are the most influential social, economic, environmental, institutional, and technical challenges to the low-carbon energy transition. Furthermore, the Netherlands was ranked first in 2015 according to its performance in dealing with the challenges of the low-carbon transition, followed by Germany; in contrast, Germany was ranked first in 2020, followed by the Netherlands. However, the significant change belonged to Spain, as it was ranked 21st in 2015 but 11th in 2020. Also, Bulgaria was ranked as the worst country according to its performance in dealing with the identified challenges.

We draw two main conclusions. Firstly, according to the proposed framework of challenges and related indicators, it can be concluded that moving toward a low-carbon future needs to consider a wide variety of challenges simultaneously, not just focusing on one pillar, such as economic challenges, since most of the countries usually deal with providing enough funds to cover transition's expenses, such as improving grids; however, an energy transition requires decision-makers to reengineer and redesign all social, economic, environmental, technical, and institutional policies, strategies, and tools. Secondly, as energy justice is ranked as the most significant social challenge to the low-carbon energy transition, it can be concluded that just energy transition is the primary solution to the social challenge, and even all challenges to the low-carbon energy transition, since just energy transition put society at the center of the energy transition, meaning that not only it brings justice to the energy transition, but also it could meet the sustainable development goals, boosting any transitions, including low-carbon energy transition. To be more specific, sustainable development goals seek to meet the needs of the present generation without adversely affecting the ability of future generations to meet their needs, which is in line with all agreements related to energy transition and climate change.

6.1 Research limitations and future recommendations

The present research faced some limitations: (1) some countries were excluded due to the missing data, including Romania, Cyprus, Croatia, and Malta; (2) Asking experts' opinions to determine subjective weights of challenges was time-consuming as experts were not familiar with linguistic variables and fuzzy logic in general, and (3) data processing and calculations were time-consuming and complicated due to the high number of identified challenges and indicators. Moreover, it is recommended to evaluate countries' performance in dealing with the identified challenges using dynamic systems or fuzzy cognitive maps to see the impact of challenges interactions on countries' performance. Also, it is recommended that the proposed integrated framework be applied under various fuzzy environments, such as spherical fuzzy sets, and the results be compared with the present study.

6.2 Policy recommendations

- The Government must proactively develop, formulate, and implement policies by eliminating discrepancies and ineffective methods.
- Authorities must develop more comprehensive policies than merely technology techniques and innovations for transitioning the energy supply from fossil fuels to low-carbon energies.
- A national plan for sustainable development should be established to evaluate and prioritize eco-friendly and sustainable mitigation and adaptation strategies.
- Social innovation methods that target cultures, institutions, energy use, and supply practices must form the foundation of national programs.
- Aside from government intervention, residents should share their knowledge and awareness of the climate condition, which can significantly help develop mitigation and adaptation strategies.
- If transition pathways do not include actions targeted at an absolute reduction in energy use, particularly at the individual level, it is impossible to guarantee sustainable development.
- Governmental authorities, institutions, and society should combine resources to design and deliver plans to reduce human interventions in nature, especially forests.

Supplementary Information

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Supplementary Material 1.

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Mahyar Kamali Saraji: Conceptualization, writing- original draft preparation, data collection, methodology, software, validation, and visualization; *Dalia Streimikiene*: Conceptualization, supervision, reviewing, and editing.

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Declarations

Competing interests
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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An analysis of challenges to the low-carbon energy transition toward sustainable energy development using an IFCM-TOPSIS approach: A case study

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ABSTRACT

As countries worldwide grapple with the urgent need to mitigate climate change, adopting low-carbon energy sources has become a top global priority. This priority is particularly emphasized in the European Union (EU), with various initiatives, policies, and regulations to promote renewable energy sources and reduce carbon emissions. Despite these efforts, the transition to a low-carbon energy future has faced several challenges, such as the high cost of renewable energy technologies, land use, and technical issues. These challenges require decision-makers to consider and address various factors to ensure sustainable and low-carbon energy development. In this context, the present study identified challenges to the low-carbon energy transition through a literature review from 2013 to 2023. The study then set out a novel intuitionistic fuzzy cognitive map method to map the interactions of identified challenges and analyze the case study performance in dealing with the challenges under three scenarios: people first, technology first, and duet. Subsequently, the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) method was applied to find the best scenario according to performance analysis. The results indicated that the most significant challenge is investment, followed by short-termism, and reformation, out of seventeen identified challenges. Results also indicated that the duet scenario was the best, and broad conclusions and policy implementations were provided according to the obtained results.
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Introduction

Low-carbon energy transitions are long-term and multidimensional, necessitating structural changes in power generation, industrial activities, and transportation networks (Nikas et al., 2020). For instance, Photovoltaic (PV) technologies have played a significant role in designing a globally sustainable energy system, with their recent spectacular performance improvement and cost reduction (Magni et al., 2022). Nevertheless, although the benefits of an effective low-carbon energy transition are widely recognized, many underlying challenges have been identified over the years. Most studies have investigated technological challenges more than others; thus, the critical role of public engagement has been disregarded. Also, public acceptance and support might influence strategy development in low-carbon energy transition, which would become severe challenges if not considered (Kim et al., 2021; Pye et al., 2019).

Public awareness could also encourage policymakers to adopt low-carbon technologies, but weak public awareness could be a severe barrier to the low-carbon energy transition; however, practical public training and general advancement in public education could enhance public awareness (Baek et al., 2019). Also, resistance to change is a serious challenge to these fundamental changes as resistance could cause public debates on the low-carbon energy transition impacts on society (Huang, 2021; Saraji et al., 2023). Energy justice is another challenge, including distributional recognition and procedural justice. Energy justice is a niche for boosting innovative alternatives and promoting a democratic energy system (Sorman et al., 2020). Energy security is the effectiveness of the energy mix given by internal and external resources, energy dependence, and investment flexibility in meeting energy requirements. A key obstacle is transitioning to a low-carbon energy system without weakening energy justice and security (Kasradze et al., 2023; Sareen & Kale, 2018).

Furthermore, a significant disparity exists between present and necessary investments in transitioning to low-carbon energy, necessitating more funding. Adopting renewables may result in declining gross domestic product or labor productivity. The absence of solid

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financial incentives may jeopardize the transition. In addition to construction, operation, and maintenance, the transition expenses include social costs from carbon emissions (Bachner et al., 2020). Due to the complexity of energy systems resulting from several technologies, spatial-temporal aspects, transporters, and high-investment infrastructure, the transition is costly (Pizarro-Irizar et al., 2020). Also, government subsidies for fossil fuels impede the transition, necessitating governments to phase off support for greenhouse gases by reducing energy use. It is claimed that fossil fuel subsidies significantly increase energy consumption; hence, eliminating subsidies will reduce CO2 emissions (Zhang et al., 2020).

Moreover, land acquisition is essential for constructing solar farms, influencing global land-use patterns, and is regarded as a distinctive feature of the global land rush. The necessary land for establishing solar farms should be of a suitable size and geographic location; despite significant investments, these lands are scarce (Govindan, 2023). In addition, biofuels may release pollutants such as particulate matter, carbon dioxide, hydrocarbons, sulfur dioxide, and nitrogen oxides; however, plants used for biomass may lower dangerous gases through photosynthesis (Chien et al., 2023). Furthermore, using raw minerals, such as lithium, cobalt, and copper, further impedes the transition, as statistics indicate a deficiency of such resources. In addition, short-termism has permeated policymaking, affecting long-term targets with short-term decisions; hence, governments must contribute to the energy transition by pursuing long-term objectives and not merely giving short-term gains (Andrews-Speed, 2016; Nochta & Skelcher, 2020).

Moreover, innovative policies are often necessary for a successful transition (Xiao et al., 2022). Therefore, authorities should acknowledge new policies addressing subsidies, standards, laws, and information flow to eliminate barriers and stimulate innovation (Rosenbloom et al., 2018). In addition, conflicts will occur throughout all energy transition phases, including political issues such as minimum tariffs that directly impact financial returns. As a result, authorities must reform their procedures and laws to deal with problems. During the transition, their responsibilities include the development of new procedures and coordination, providing necessary materials, establishing rules, and management (Kern & Rogge, 2018). On top of that, an explicit set of norms and regulations directs the energy supply along a preset course. It is claimed that the absence of specific standards is a significant obstacle to the transition to low-carbon energy (Wu et al., 2020). A rising share of renewables also impacts the stability of the current grid since innovative technologies are needed for decarbonization; nevertheless, a shortage of infrastructure could slow the energy transition (Bachner et al., 2020).

Some studies are closely related to the present research regarding the applied method and field of study. For instance, K. Papageorgiou et al. (2020) applied Fuzzy Cognitive Maps (FCMs) in the decision-making process for PV solar energy sector development. This study investigated certain factors and their influence on Brazilian PV solar energy development with the help of FCMs. Also, Alipour et al. (2019) applied FCMs to analyze solar energy development nationally in Iran. They studied the characteristics and dynamics of solar technology deployment in Iran in an uncertain environment using FCMs. Jetter and Schweinfort (2011) applied FCMs to investigate the feasibility of the proposed approach with two scenario studies on solar PV panels. A new approach to scenario building, which involves fuzzy cognitive maps, is suggested in this article. This method combines intuitive, cognitive mapping techniques with formal, quantitative analysis.

As mentioned, the low-carbon energy transition has faced many challenges and difficulties over the years. Therefore, many countries have aimed to move toward decarbonization, requiring them to consider the mentioned challenges in their context and develop specific scenarios to deal with difficulties identified based on the current situation of their energy system (Saraji & Streimikiene, 2023). To this end, the present study investigated the energy system's performance under three scenarios using integrated Intuitionistic Fuzzy Cognitive Maps (IFCMs) and the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) method. IFCMs are an extension of FCMs that integrate intuitionistic fuzzy set theory to account for uncertainty and hesitation in concept relationships. Nodes represent concepts, while directed edges depict causal links. IFCMs utilize intuitionistic fuzzy values, such as membership, non-membership, and hesitation degrees. The activation function updates node states, offering a detailed representation of intricate systems in decision-making and knowledge representation (E. I. Papageorgiou & Iakovidis, 2012). TOPSIS is a methodology that assesses each option based on multiple criteria and computes the distance of each option to the ideal and anti-ideal solutions. The ideal solution signifies the highest benefit for each criterion, while the anti-ideal solution represents the minimum acceptable values. The technique then grants a proximity score to each alternative, reflecting its resemblance to the ideal solution and contrast to the anti-ideal solution. The option with the highest TOPSIS score is deemed the most favorable selection (Kamali Saraji & Streimikiene, 2022). The main contributions of the present study are listed below:

- To identify challenges to the low-carbon energy transition. It is imperative for organizations and governments to proactively identify and anticipate potential challenges to develop effective strategies to overcome them. The strategy development may involve setting clear and specific objectives, establishing realistic timelines, and allocating resources efficiently to address the identified obstacles. By doing so, they can enhance their overall preparedness and optimize their chances of success in achieving their goals.
- To map the interactions between the identified challenges using an intuitionistic fuzzy cognitive map. The decision-making process can be significantly enhanced by integrating FCMs, allowing for a more comprehensive and accurate understanding of real-world dynamics by considering factors like uncertainty, ambiguity, and multidimensional relationships. This approach can prove particularly useful in strategy formulation, systems thinking, and decision-making, as a more nuanced perspective of the intricate relationships and interdependencies within complex systems can be gained with FCMs, allowing for better-informed decisions with greater precision and confidence.
- To develop scenarios to analyze the performance of the case study's energy system under different assumptions. An effective way to evaluate an energy system in a given case study is to create various scenarios based on different assumptions. This approach allows for a holistic and proactive assessment, enabling stakeholders to make informed strategic decisions. Risks can be minimized by considering a range of potential scenarios. At the same time, innovation and the growth of sturdy and flexible energy systems can be promoted. Overall, this approach offers a comprehensive and forward-thinking way to approach energy system evaluation and planning.
- To rank developed scenarios using TOPSIS to find the best scenario. TOPSIS is a valuable method that enables decision-makers to assess the most impactful scenario based on various criteria and considerations. This approach is highly beneficial as it provides an objective and transparent process for evaluating trade-offs and supporting quantitative comparison. Utilizing TOPSIS simplifies the decision-making process when dealing with complex scenarios, ensuring that all factors are considered before making a final decision. Its use facilitates a balanced analysis of multiple options and can help to identify the most suitable course of action. Overall, TOPSIS is a powerful tool that can aid in developing practical solutions while ensuring that decision-making remains fair, transparent, and informed.

The structure of the present paper is as follows: Section two presents the case study. The methodology is presented in section 3.

Results are shown and illustrated in section 4 and discussed in section 5. Section 6 presents broad conclusions on results.

Case study: Lithuania

Lithuania was one of the EU's first countries to stop importing gas from Russia. Moreover, Lithuania has faced many social, economic, technological, environmental, and institutional challenges impacting the energy sector over the years, motivating the present research to investigate Lithuania's current situation according to the identified challenges. The present study reviewed the literature to identify challenges from 2013 to 2023. Table 1 shows the identified challenges and their related indicators. In order to develop Table 1, a new technique, PSALSAR, was used with six main steps: Protocol, Search, Appraisal, Synthesis, Analysis, and Report, presented below:

- Step 1: Research protocol. Ensuring transparency, reproducibility, and a systematic approach in evaluating literature is crucial to reducing subjectivity in any study. At this stage, it is essential to define the scope of the current research, develop research

Table 1
Challenges and related indicators that have been found through literature review

Challenges	Indicator	References
Public engagement	1. Share of zero-emission vehicles in newly registered passenger cars – % 2. Greenhouse gas emissions per capita – kg CO2eq/person 3. GHG intensity of power & heat generation – t CO2eq /Million EUR 4. Average CO2 emissions of new passenger cars – g CO2/km	Chilvers and Longhurst (2016), Pilpola and Lund (2018), Ryghaug ewt al. (2018)
Public awareness	1. The general advancement of knowledge: R&D financed from General University Funds (GUF) – Million Euro 2. The general advancement of knowledge: R&D financed from other sources than GUF – Million Euro	Andrews-Speed (2016), Gössling and Scott (2018), (Govindan, 2023)
Public resistance	1. Share of renewable energy in gross final energy consumption – % 2. Renewable energy share in transport (RES-T) – % 3. Renewable electricity share (RES-E) – % 4. Renewable energy for heating & cooling (RES-H&C) – % 5. Fossil fuel avoidance by renewable energy – %	(Baker & Phillips, 2019); Ringrose (2017), Urban and Nordensvärd (2018),
Energy justice	1. Energy affordability – % 2. Harmonized index of consumer prices – % 3. Inability to keep home adequately warm – % 4. Household electricity prices – EUR/kWh 5. Household gas prices – EUR/kWh	Healy and Barry (2017), Newell and Phillips (2016), Mundaca et al. (2018), Schmid et al. (2017)
Labor transition	1. Total employment in renewables – employed persons (1000)	Fragkos and Paroussos (2018),
Energy security	1. Aggregate supplier concentration index (from extra-EEA suppliers) – (0 – 1000) 2. Net import dependency – % 3. N-1 rule for gas infrastructure – % 4. Electricity interconnection %– 5. Market concentration index - power generation – (0-10000) 6. Market concentration index - wholesale gas supply – (0-10000) 7. Available energy, energy supply, and final energy consumption per capita – kilograms of oil equivalent (KGOE) per capita	Hoggett (2014), Sareen and Kale (2018), Sovacool and Saunders (2014), La Viña, Tan, Guanzon et al., 2018
Investment	1. Companies producing at least 5 % of the net electricity generation – Number 2. Companies with at least 5 % of the electricity generation – % 3. Companies with at least 5 % of the electricity capacity – % 4. Electricity retailers – Number 5. Gross domestic product at market prices	Bolton and Foxon (2015), Hall et al. (2016), Newell and Phillips (2016), Schinko and Komendantova (2016),
Mitigation and adaptation costs	1. GHG avoided emissions due to renewable energy – % vs. 2005 (2005=0.0 %) 2. Greenhouse gas emissions reductions (the base year 1990) – (0-100) 3. GHG Intensity of Energy [kg CO2 eq./toe] 4. Greenhouse gas intensity of the economy – t CO2eq /Million EUR 5. Energy productivity – Euro per kilogram of oil equivalent (KGOE)	Nikas et al. (2018); Schinko and Komendantova (2016), Urban and Nordensvärd (2018)
Subsidies	1. Fossil Fuel Subsidies – USD 2. Total environmental taxes – USD	Åhman et al. (2017), Li et al. (2020), Urban and Nordensvärd (2018), Shem et al. (2019)
Land use	1. Land Use – Square kilometer 2. Land cover – Square kilometer	Hildingsson and Johansson (2016), Sareen and Kale (2018)
Pollutions	1. Landfill rate of waste excluding major mineral wastes – %	Hildingsson and Johansson (2016), Nikas et al. (2018)
Resource consumption	1. Raw material consumption (RMC) – Thousand tonnes	Bachner et al. (2020), Ioannidou et al. (2020); Seck et al. (2020)
Short-termism	1. Imports of electricity and derived heat by partner country – Gigawatt-hour 2. Imports of natural gas by partner country – Million cubic meters 3. Imports of oil and petroleum products by partner country 4. Imports of solid fossil fuels by partner country	Andrews-Speed (2016), Åhman et al. (2017), Rogge and Johnstone (2017)
Innovative policies	1. Patent on ENV technologies – Patents per million habitants 2. Patents on Energy Union priorities – Patents per million habitants	Haarstad (2016), Urban and Nordensvärd (2018)
Reformations	1. Environmental policies – Number	Wakiyama et al. (2014), Rogge and Johnstone (2017)
Technical Standards	2. Total government budget allocations for R&D – Million Euro	Gössling and Scott (2018), Rosenbloom et al. (2018), Wu et al. (2020)
Infrastructure	1. Transport, telecommunication, and other infrastructures – Million Euro 2. New electricity capacity connected – Megawatt 3. Gross electricity production – Hydro-Gigawatt-hour 4. Gross electricity production – Wind-Gigawatt-hour 5. Gross electricity production – Solar-Gigawatt-hour(I_{53})	Ćetković and Buzogány (2016), Muinzer and Ellis (2017); Power et al. (2016)

questions, and determine the most appropriate strategies to achieve the study's objective. The primary research which the systematic review addressed is: What impediments and obstacles are encountered in implementing the low-carbon energy transition?
- Step 2: Searching. Developing and executing an effective search strategy is crucial. Choosing a suitable database is imperative to ensure high-quality literature and a comprehensive coverage of available papers. Consequently, the following research strings were utilized to retrieve all articles indexed on Scopus and Web of Science:

Scopus: TITLE-ABS-KEY (("low carbon energy transition") OR ("low carbon transition") OR ("green energy transition") OR ("just energy transition") OR ("renewables" AND "energy transition")) OR ("challenge" AND "renewable" AND "energy transition"))

WOS: All = ((low carbon energy transition) OR (low carbon transition) OR (just energy transition) OR (green energy transition) OR (renewables AND energy transition) OR (renewables AND energy transition) OR (challenge AND renewable AND energy transition))

- Step 3. Appraisal. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol has been used to select articles that meet the search criteria by the current research objectives. Only publications that satisfy the search criteria have been chosen. To be included, the articles must meet two criteria: firstly, the search keywords must appear in the title, abstract, or keywords, and secondly, the articles must have been published in a peer-reviewed scientific journal. Also, the following requirements apply to exclusion: review papers, editorial letters, chapter books, conference proceedings, academic theses, non-English language studies, and duplicated publications.
- Step 4. Synthesis. The collected data has been split into two categories: general and specific. General information includes the year of publication, journals, case study location, and future directions. On the other hand, specific information covers research gaps, objectives, and outcomes.
- Step 5. Analysis. This step's primary focus is finding solutions to the fundamental research questions and examining the classified information related to the research needs.
- Step 6. Report. This step involves highlighting the critical aspects of step 5. The literature review findings are summarized in the 27-point checklist of the PRISMA statement. The following results of the systematic review are presented in detail.

The share of zero-emission vehicles in a newly registered passenger car was 1.1 % in Lithuania, while the same stat for the Netherlands, ranked first, is 20.2 %. Also, stats for greenhouse gas emissions per capita, GHG intensity of power and heat generation, and average CO2 emissions of new passenger cars were 7.24 (kg CO2eq/person), 1.03 (t CO2eq /Million EUR), and 128.9 (g CO2/km), respectively. However, Sweden had the least greenhouse gas emissions per capita and GHG intensity of power and heat generation compared to other countries in the EU, with 4.86 (kg CO2eq/person), 0.4 (t CO2eq /Million EUR), while the Netherlands had the least average CO2 emissions of new passenger cars, with 105.5 (g CO2/km). On top of that, stats for the share of renewable energy in gross final energy consumption, renewable energy share in transport, and renewable energy for heating and cooling were 25.46 %, 4.05 %, and 47.36 %, while the same stats for Sweden, ranked first, were 56.39 %, 30.31 %, and 66.12 %, respectively. In addition, the stat for renewable electricity share in Lithuania was 18.80 %, while the stat for Austria, ranked first, was 75.14 %. Fossil fuel avoidance by renewable energy for Lithuania was 9.06 %, while the same stat for Sweden, ranked first, was 39.8 %. Also, regarding public education and awareness, R&D financed from General University Funds (GUF) and R&D funded from other sources than GUF were 85.58 (million EUR) and 18.26 (million EUR), while the same stats for Germany, ranked first, were 13998.65 and 5630.83 (million EUR).

Moreover, regarding indicators connected to energy justice, Lithuania's stats for energy affordability, harmonized index of consumer prices, inability to keep home adequately warm, household electricity prices, and household gas prices were 11.46 %, 5.67 %, 38.4 %, 0.13 EUR/kWh, and 0.04 EUR/kWh respectively. However, Sweden's stat for energy affordability was 3.17 %, the lowest percentage in the EU. Also, the lowest percentage for the harmonized index of consumer prices belonged to Luxembourg, with 3.14 %, and the lowest percentage for the inability to keep home adequately warm belonged to Finland, with 4.3 %. In addition, the household electricity price in Bulgaria, the lowest number in the EU, was 0.1 EUR/kWh, and the household gas price in Hungary, the lowest number in the EU, was 0.03 EUR/kWh. Furthermore, regarding energy security indicators, Lithuania's aggregate supplier concentration index stat was 47.75 out of 1000. The same stat for the best country (Slovenia) was 1.63, and net import dependency for Lithuania was 75.22 %; however, the same stat for Estonia (the best country) was 4.83 %. Electricity interconnection for Lithuania was 77 %, while the same stat for the best country (Poland) was 3.94 %, and the market concentration indexes for both power generation and wholesale gas supply were 3784.04 and 6375.52 out of 10,000; however, the same stats for best countries (Germany and Ireland) were 316.75 and 1,287.66, respectively. On top of that, the total number of people employed in the renewables industry was 11.9 per 1000 persons, and the same stat for Germany was 673.5.

Moreover, regarding the economic indicators, the number of companies producing at least 5 % of the net electricity generation, the percentage of companies with at least 5 % of the electricity generation, and the percentage of companies with at least 5 % of the electricity capacity in Lithuania were 3, 43.6 %, and 53 %. However, the same statistics were found for Germany and Slovenia: 5, 92.56 %, and 87 %. Also, the number of electricity retailers and gross domestic product at market prices for Lithuania were 24 and 49507.2, and the same stats for Germany were 1421 and 3405430. Furthermore, mitigation and transition cost indicators for Lithuania were: 20.6347 % for GHG-avoided emissions due to renewable energy, 41.75 out of 100 for greenhouse gas emissions reductions, 2665.71(Kg CO_2/ton) for GHG intensity of energy, and 466.97 (t CO2eq /Million EUR) for GHG intensity of the economy. On top of that, Lithuania's stats for energy productivity (Euro per kilogram of oil equivalent), fossil fuel subsidies, and total environmental taxes were 13.9 KGOE, 254,853,371 $, and 921.4 $; however, the same stats for Estonia, Slovakia, and Germany were 22.61 KGOE, 2,284,393 $, and 61,112.71 $. Moreover, regarding environmental indicators, Lithuania's stats for land use (m^2), land cover (m^2), landfill rate of waste excluding major mineral wastes, and raw material consumption (thousand tonnes) were 65284 m^2, 1392 m^2, 17 %, and 58262.4 thousand tonnes, respectively. However, Luxembourg's stat for land use was 2595 m^2, France's stat for land cover was 30893 m^2, Denmark's stat for landfill rate of waste excluding major mineral wastes was 1 %, and Luxembourg's stat for raw material consumption was 17044.87 thousand tonnes, as the best countries according to environmental indicators.

In addition, regarding institutional indicators, Lithuania's stat for imports of electricity and derived heat was 12013.4 Gigawatt-hour; imports of natural gas was 2862.1 million cubic meters, imports of oil and petroleum was 8945.1 thousand tonnes, and imports of solid fossil fuels was 194.1 thousand tonnes. However, Luxembourg's stat for imports of electricity and derived heat was 17044.87 Gigawatt-hour, Ireland's stat for imports of natural gas was 1761.11 million cubic meters, Estonia's stats for imports of oil and petroleum was 447 thousand tonnes, and Latvia's stats for imports of solid fossil fuels was 1,978.42 thousand tonnes. Moreover, regarding anti-innovation policies, Lithuania's stat for patents on environmental technologies (patents per million habitants) was 6.91, patents on Energy Union priorities (patents per million habitants) was 0.63, for environmental policies (No.) was 12, and total government budget allocations for R&D was 174.801 million Euro. However, Denmark's stat for patents on environmental technologies was 21.96, and for patents on Energy Union priorities 54.36. Spain's stat for environmental policies was 31, and Germany's stat for total government budget allocations for R&D was 39,158.42 million Euros. On top of that, regarding indicators connected to infrastructure, Lithuania's stat for transport, telecommunication, and other infrastructure (million Euro) was 6.12 million Euro, while the same stat for France was 1,538.5. Also, Lithuania's stat for new electricity capacity connected was 113 megawatts. Gross electricity production for hydro, wind, and solar was 1080.1, 1,551.7, and 128.8 Gigawatt/hour, respectively. However, the gross electricity production for Sweden was 72,440 gigawatts/hour, the gross electricity production for Germany was 132,102 gigawatts/hour, and the gross electricity production for Germany was 48,641 gigawatts/hour.

Research method

The integration of FCM and TOPSIS has been rarely used in the literature. For instance, Baykasoğlu and Gölcük (2015) developed a novel multiple-attribute decision-making model via fuzzy cognitive maps and hierarchical fuzzy TOPSIS to deal with a multicriteria problem in higher education systems. The Strengths, Weaknesses, Opportunities, and Threats (SWOT)-based strategy selection problem incorporates the proposed model to demonstrate its practicality. Also, Salmeron et al. (2012) ranked fuzzy cognitive map-based scenarios with TOPSIS. The authors' proposal introduces a model that enables decision-makers and policy-makers to assess the effects of interactions between entities. The proposed methodology represents an improvement over traditional scenario-based decision-support tools by combining the Delphi method, soft computing (fuzzy cognitive maps), and multicriteria (TOPSIS) techniques. The present study applied an integrated IFCM-TOPSIS approach to investigate Lithuania's progress toward a low-carbon energy transition. The research steps are:

- Step 1. Finding the challenges to the low-carbon energy transition and related indicators through a literature review
- Step 2. Asking experts to draw their mind maps under Intuitionistic fuzzy sets
- Step 3. Integrating individual maps and determining different features of aggregated fuzzy maps, such as centrality, using FCMapper vs. 1
- Step 4. Scenario planning for the case of Lithuania
- Step 5. Evaluating the performance of Lithuania under developed scenarios using IFCM equations
- Step 6. Applying TOPSIS to rank scenarios.

Preliminaries

Definition 1. (E. I. Papageorgiou & Iakovidis, 2012): Let $X \neq \emptyset$ a given set; thus, an IFS in X is an object A shown below:

$$\tilde{A} = \{ \langle x, \mu_{\tilde{A}}(x), \nu_{\tilde{A}}(x) \rangle ; x\epsilon X\} \tag{1}$$

Where $\mu_{\tilde{A}}(x)$ *and* $\mu_{\tilde{A}}(x) : X \to [0, 1]$, and $0 \leq \mu_{\tilde{A}}(x) + \mu_{\tilde{A}}(x) \leq 1$. Also, the hesitancy degree for each $x \in X$ is equal to $1 - \left(\mu_{\tilde{A}}(x) + \mu_{\tilde{A}}(x)\right)$.

Definition 2. (E. I. Papageorgiou & Iakovidis, 2012): Let $\tilde{A}$ and $\tilde{B}$ two IFSs. Thus, the Euclidian distance between $\tilde{A}$ and $\tilde{B}$ is calculated using equation 2.

$$d\left(\tilde{A}, \tilde{B}\right) = \sqrt{\frac{1}{2}\sum_{i=1}^{n}\left(\mu_{\tilde{A}}(x) - \mu_{\tilde{B}}(x)\right)^2 + \left(\nu_{\tilde{A}}(x) - \nu_{\tilde{B}}(x)\right)^2 + \left(\pi_{\tilde{A}}(x) - \pi_{\tilde{B}}(x)\right)^2} \tag{2}$$

Definition 3. (Iakovidis & Papageorgiou, 2010): Let $\tilde{A}$ and $\tilde{B}$ two IFSs. Thus, the following equations present some operators for IFSs.

$$\overline{A} = \{ \langle x, \nu_{\tilde{A}}(x), \mu_{\tilde{A}}(x) \rangle ; x\epsilon X\} \tag{3}$$

$$\tilde{A} \cap \tilde{B} = \{x, \min(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)), \max(\nu_{\tilde{A}}(x), \nu_{\tilde{B}}(x)) | x \in X\} \tag{4}$$

$$\tilde{A} \cup \tilde{B} = \{ \langle x, \max(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)), \min(\nu_{\tilde{A}}(x), \nu_{\tilde{B}}(x)) \rangle | x \in X\} \tag{5}$$

$$\tilde{A} + \tilde{B} = \{ \langle x, \mu_{\tilde{A}}(x) + \mu_{\tilde{B}}(x) - \mu_{\tilde{A}}(x).\mu_{\tilde{B}}(x), \nu_{\tilde{A}}(x).\nu_{\tilde{B}}(x) \rangle | x \in X\} \tag{6}$$

$$\tilde{A} - \tilde{B} = \{ \langle x, \mu_{\tilde{A}}(x) + \mu_{\tilde{B}}(x), \nu_{\tilde{A}}(x) + \nu_{\tilde{B}}(x) - \nu_{\tilde{A}}(x).\nu_{\tilde{B}}(x) \rangle | x \in X\} \tag{7}$$

$$n\tilde{A} = \left\{ \langle x, 1 - (1 - \mu_{\tilde{A}}(x))^n, (\nu_{\tilde{A}}(x))^n \rangle ; x\epsilon X\right\} \tag{8}$$

Definition 4. (Wang & Liu, 2012): Intuitionistic Fuzzy Einstein Weighted Averaging Operator (IFWA).

Let $\alpha_j = (\mu_{\alpha_j}, \nu_{\alpha_j}), (j = 1, 2, \ldots, n)$ be a collection IFSs in and $\omega = (\omega_1, \omega_2, \ldots, \omega_n)$ is the weight vector of $\alpha_j = (j = 1, 2, \ldots, n)$ such that $\omega_j \in [0, 1], j = 1, 2, \ldots, n$ And $\sum_{j=1}^{n}\omega_j = 1$; then an $IFWA^{\varepsilon}$ operator of the dimension n is a mapping $IFWA^{\varepsilon} : (L^*)^n \to L^*$ and equation 9 calculates $IFWA^{\varepsilon}_{\omega}$.

$$IFWA^{\varepsilon}_{\omega}(\alpha_1, \alpha_2, \ldots, \alpha_n) = \left(\frac{\left(1 + \mu_{\alpha_{k+1}}\right)^{\omega_{k+1}} - \left(1 - \mu_{\alpha_{k+1}}\right)^{\omega_{k+1}}}{\left(1 + \mu_{\alpha_{k+1}}\right)^{\omega_{k+1}} + \left(1 - \mu_{\alpha_{k+1}}\right)^{\omega_{k+1}}}, \frac{2\upsilon_{\alpha_{k+1}}^{\omega_{k+1}}}{(2 - \nu_{\alpha_{k+1}}) - (\upsilon_{\alpha_{k+1}}^{\omega_{k+1}})}\right) \tag{9}$$

Intuitionistic fuzzy cognitive map (IFCM)

A fuzzy cognitive map (FCM) is a tool originating from networks and fuzzy logic, which might be used for forecasting, research development, and scenario planning (Dursun & Gumus, 2020). The other concepts' influence determines the value of each concept using equation 10:

$$A_i^{(k+1)} = f\left(A_i^{(k)} + \sum_{\substack{i \neq j \\ j=1}}^{N} A_i^{(k)}\omega_{ji}\right) \tag{10}$$

Where the value of concept C_i is shown by $A_i^{(k)}$ is at the k[th] iteration, ω_{ji} is the weight of the connection from C_j to C_i, and the threshold function is f(). However, due to the drawbacks of FCM, a new extension called IFCM was proposed, and its steps are:

Step 1. Concept nodes (C_i i = 1,2, . . ., N) should be identified in the first step. In the present study, these concepts were identified through a literature review.
Step 2. Concepts could interact in three ways: positive, negative, or null, decided by experts.
Step 3. The intuitionistic fuzzy numbers represent the strength of causal interactions. Subsequently, membership, non-membership, and hesitation values are determined.
Step 4. The weight matrix is determined using support from experts.
Step 5. The iterative equation 11 should be applied until all factor weights are steady.

$$A_i^{(k+1)} = f\left(A_i^{(k)} + \sum_{\substack{i \neq j \\ j=1}}^{N}\left(A_i^{(k)}\omega_{ji}^{\mu} - A_i^{(k)}\omega_{ji}^{\pi}\right)\right) \tag{11}$$

Where the value of concept C_i at the k^{th} and (k^{th} +1) iterations are $A_i^{(k)}$ and $A_i^{(k+1)}$. f() is the threshold function. In this research, a sigmoid function is used. Membership and hesitation values of causal links are shown by ω_{ji}^{μ} and ω_{ji}^{π}.

Step 6. After some iterations, all concept values converge.

Features of a cognitive map

Each cognitive map has features below (Gray et al., 2013):

- Density: Number of connections compared to all possible connections
- Transmitter: Variables that only impact the system
- Receiver: Variables that only are impacted by the system
- Ordinary: Variables that impact the system and are impacted by the system
- Indegree: Indegree is the column sum of absolute values of a variable and shows the cumulative strength of variables entering the unit
- Outdegree: Outdegree is the row sum of absolute values of a variable in the adjacency matrix and shows how much a given variable influences other variables
- Centrality: The conceptual importance of individual concepts. The higher the value, the greater the importance. Centrality is a sum of relationship value, meaning indegree and outdegree.

Topsis

After setting the initial values in Equation 10, the final value for each challenge was determined after several iterations. Afterward, the best scenarios according to final values are selected in this step. To this end, the TOPSIS, a multicriteria decision analysis method, is used; the TOPSIS steps are presented below in detail (Ciardiello & Genovese, 2023; Saraji et al., 2021).

Step 1. Constructing a weighted decision-making matrix

In order to rank scenarios according to challenges, it is necessary to construct a weighted decision-making matrix. In the present study, the centrality of each challenge is considered as weight. The centrality of each challenge is the difference between inputs and outputs for each challenge. It should be noted that centrality values should be normalized using Equation 11. Then, Equation 12 calculates the weighted decision-making matrix, subject to $\sum_{j=1}^{n} W_j = 1$.

$$w_j = \frac{Cen_j}{\sum_{j=1}^{m} Cen_j} \tag{11a}$$

$$Nor.Value_{ij} = Fin.Value_{ij} * w_j \tag{12}$$

Where w_i is the normalized centrality for i=1,..., m; $Nor.Value_{ij}$ is the normalized value for scenario i according to challenge j, and $Fin.Value_{ij}$ is the final value for scenario i according to the challenge j obtained after running the IFCM model for several iterations.

Step 2. PIS and NIS determination

The positive and negative ideal solutions are determined in this step. To this end, equations 13 and 14 are used.

$$\text{PIS} = \left\{ \left(\max_i Nor.Value_{ij} | j \in J \right), \left(\min_i Nor.Value_{ij} | j \in J' \right) | \ i = 1, \ldots, \ m \right\}$$
$$= \{ \text{PIS}_1^+, \ \text{PIS}_2^+, \ \ldots, \ \text{PIS}_n^+ \} \tag{13}$$

$$\text{NIS} = \left\{ \left(\min_i Nor.Value_{ij} | j \in J \right), \left(\max_i Nor.Value_{ij} | j \in J' \right) | \ i = 1, \ldots, \ m \right\}$$
$$= \{ \text{NIS}_1^-, \ \text{NIS}_2^-, \ \ldots, \ \text{NIS}_n^- \} \tag{14}$$

Where $J = \{j = 1, 2, \ldots, n | j \ associated \ with \ the \ benefit \ criteria\}$, and $J' = \{j = 1, 2, \ldots, n | j \ associated \ with \ the \ cost \ criteria\}$.

Step 3. The Separation Measure Calculation

Equations 15 and 16 calculate the separation measure for each alternative.

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(Nor.Value_{ij} - \text{PIS}_j^+ \right)^2} \ (i = 1, \ldots, \ m) \tag{15}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(Nor.Value_{ij} - \text{NIS}_j^- \right)^2} \ (i = 1, \ldots, \ m) \tag{16}$$

Step 4. Relative Closeness Calculation

Equation 17 calculates the relative closeness to the ideal solution.

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^+}, \ 0 < C_i^* < 1, \ i = 1, \ldots, \ m \tag{17}$$

Where $C_i^* = 1 \ if \ A_i = A^+$, and $C_i^* = 0 \ if \ A_i = A^-$.

Step 10. Ranking

The descending order of C_i^* shows alternatives' rank.

Results

After identifying the challenges through a literature review, three experts were asked to draw the interactions between challenges and specify their strengths using linguistic variables. Tables 2-4 show experts' evaluation of challenges' interactions. The three individuals designated as experts in this particular context were all distinguished academics possessing a wealth of knowledge and experience in their respective fields. In order to qualify for this role, each expert was required to have at least a master's degree in economics or a related discipline, as well as a minimum of five years of professional experience working within the energy sector. Such qualifications ensured that the experts were well-equipped to provide informed and insightful guidance on energy policy and economics matters.

Abbreviations: H: high (0.95,0.05); L: low (0.7,0.25); M: medium (0.50,0.40); VH: very high (0.25,0.70); VL: very low (0.05,0.95); N: negative effect.

After collecting experts' opinions and turning linguistic terms into fuzzy numbers, Equation 9 was applied to aggregate individual mind maps. The aggregated matrix is shown in Table 5.

Afterward, the aggregated matrix was imported into FCMapper Vs. 1 for further analysis, and Table 6 shows the results obtained.

Also, the density of the map is 0.9412, and the total number of connections is 272. It should be noted that all 17 challenges are ordinary.

Scenario planning

After determining the interactions between concepts, three scenarios are developed to analyze the low-carbon energy transition in Lituania. Indicators might be assigned various values between 0 to 1. After setting values to each indicator, the intuitionistic fuzzy map,

Table 2
Interactions between challenges given by the expert 1

E1	Public engagement	Public awareness	Public resistance	Energy justice	Labor transition	Energy security	Investment	Mitigation	Subsidies	Land use	Pollutions	Resource consumption	Short-termism	Innovative policies	Reformations	Technical Standards	Infrastructure
Public engagement	0	0	NH	0	VL	0	M	NVL	0	L	0	0	M	VL	H	0	0
Public awareness	VH	0	VH	VL	L	L	H	0	VL	NVL	NVL	NVL	L	VL	VL	VL	VL
Public resistance	NVH	NVH	0	0	NH	0	NVH	0	0	NVH	0	0	H	NH	NH	0	0
Energy justice	VH	VH	VH	0	L	H	L	L	L	0	0	L	H	NH	NH	NL	0
Labor transition	NH	0	H	NL	0	0	0	0	0	0	0	0	NH	NH	NM	0	0
Energy security	M	0	NM	H	L	0	H	L	H	L	L	L	H	H	M	H	H
Investment	VH	VH	_H	VH	H	H	0	NH	NH	H	NH	NH	NH	H	H	H	VH
Mitigation and adaptation costs	NH	NH	H	NM	0	NM	NM	0	H	NVL	L	L	L	L	L	L	0
Subsidies	NH	NH	M	VH	H	VH	NVH	NH	0	H	H	H	VH	H	VH	VH	VH
Land use	NH	NH	VH	NH	NL	NL	NL	H	L	0	VH	VH	VH	L	L	L	L
Pollutions	NVH	NL	VH	NM	NL	NH	NH	H	0	0	0	H	H	H	H	H	L
Resource consumption	NH	NH	H	NH	0	NH	NM	M	M	M	VH	0	VH	M	M	M	0
Short-termism	NVL	NL	NL	L	L	L	L	NL	H	H	H	H	0	NVH	NVH	NVL	0
Innovative policies	VH	VH	NM	VH	H	VH	VH	NM	NM	NM	NM	NH	NH	0	VH	H	VH
Reformations	H	M	NM	L	L	M	M	NVL	L	NVL	NVL	NVL	NM	VH	0	L	L
Technical Standards	H	M	NVL	M	VL	M	M	NL	VL	NVL	NVL	NVL	NVL	M	M	0	H
Infrastructure	VH	M	NL	VH	M	H	H	NL	L	NL	NL	NL	NL	H	H	H	0

Table 3
Interactions between challenges given by the expert 2

E2	Public engagement	Public awareness	Public resistance	Energy justice	Labor transition	Energy security	Investment	Mitigation	Subsidies	Land use	Pollutions	Resource consumption	Short-termism	Innovative policies	Reformations	Technical Standards	Infrastructure
Public engagement	0	H	NM	VL	L	L	H	NL	H	NL	NL	NL	NL	VH	VH	VH	L
Public awareness	H	0	NH	H	M	H	H	NVL	L	NL	NVL	NVL	NVL	H	H	M	M
Public resistance	NH	NH	0	H	M	M	NM	H	H	NVH	NVH	NVH	H	NH	NH	NH	NVL
Energy justice	VH	VH	NH	0	L	M	M	NL	NM	NM	0	NM	NVL	L	L	L	L
Labor transition	L	L	NL	L	0	L	L	0	H	0	0	0	H	0	H	L	0
Energy security	H	M	NM	M	M	0	M	NVL	M	VL	VL	L	M	M	M	M	M
Investment	H	H	NH	H	H	H	0	NL	NVL	NVL	NVL	NVL	NVL	H	H	H	VH
Mitigation and adaptation costs	NL	NL	VH	NVH	NVH	NVH	NVH	0	H	0	0	0	VH	NM	NM	NM	NM
Subsidies	NM	NM	VL	M	M	M	NVL	NVL	0	0	0	0	M	NM	NVL	NVL	0
Land use	NH	NH	M	NL	)	NH	NVL	M	M	0	VH	VH	H	NVH	NVH	NVL	NVL
Pollutions	NVH	NVH	H	NH	NVL	NVL	NH	H	H	VL	0	0	VH	NM	NVL	NM	NVL
Resource consumption	NM	NM	M	NVL	NVL	NVL	NVL	VL	VL	VH	VH	0	VH	NVL	NVL	NVL	NVL
Short-termism	NVL	NVL	VL	NVL	NVL	NVL	NVL	M	M	M	L	L	0	NH	NH	L	L
Innovative policies	H	H	NH	H	M	M	M	NL	NL	NL	NL	NL	NL	0	H	H	H
Reformations	M	M	NM	M	M	M	H	NVL	NVL	NL	NL	NL	NL	M	0	M	M
Technical Standards	H	H	NH	H	H	H	H	NVL	L	NVH	NVH	NL	NL	H	H	0	H
Infrastructure	H	H	NVL	H	H	H	H	NL	L	NL	NL	NL	NL	H	H	H	0

Table 4
Interactions between challenges given by the expert 3

E3	Public engagement	Public awareness	Public resistance	Energy justice	Labor transition	Energy security	Investment	Mitigation	Subsidies	Land use	Pollutions	Resource consumption	Short-termism	Innovative policies	Reformations	Technical Standards	Infrastructure
Public engagement	0	M	NM	M	M	M	M	NM	VL	NL	NL	NL	VL	VL	VL	VL	L
Public awareness	VH	0	NVH	VH	H	H	H	NH	M	NH	NH	NH	NH	H	H	H	H
Public resistance	NH	NH	0	VL	VL	VL	NL	L	L	NL	H	NL	VH	NL	0	0	0
Energy justice	M	M	NM	0	M	M	M	NM	VL	NM	NM	NM	VL	VL	VL	VL	VL
Labor transition	VL	VL	VH	L	0	VL	VL	H	VL	VL	VL	VL	M	M	M	M	VL
Energy security	H	H	NH	H	H	0	VH	NH	M	NM	NM	NM	VL	VL	VL	VL	VH
Investment	VH	VH	NM	VH	VH	VH	0	NVH	NVH	NVH	NH	NH	NVL	VH	VH	VH	VH
Mitigation and adaptation costs	NVL	NVL	H	NVL	NVL	NVL	NVL	0	NVL	L	L	L	M	NVL	VL	VL	VL
Subsidies	M	M	M	NVL	M	M	M	NL	0	NL	NL	NL	NL	NL	NL	NL	VL
Land use	NL	L	VH	VL	VL	VL	VL	M	M	0	)	H	M	M	H	H	M
Pollutions	NVH	NVH	VH	NVL	NVL	NVL	NVL	L	L	L	0	L	L	NVL	NVL	L	L
Resource consumption	NVL	NVL	M	NL	NL	NL	NL	M	M	M	M	0	H	NVL	VL	VL	VL
Short-termism	NL	NL	NH	NL	NL	NL	M	M	M	H	H	H	0	NM	NM	NM	NH
Innovative policies	H	H	VH	M	M	M	H	NVL	L	NH	NH	NH	NH	0	M	M	H
Reformations	VH	VH	VH	H	H	H	VH	NM	NM	NM	NM	NM	NM	H	0	H	H
Technical Standards	H	H	NL	M	M	M	M	NL	M	NM	NM	NM	NM	H	H	0	H
Infrastructure	M	M	VL	M	M	M	H	NVL	L	H	M	M	M	M	M	M	0

Table 5
Aggregated matrix showing the aggregation of three expert's opinions

	Public engagement	Public awareness	Public resistance	Energy justice	Labor transition	Energy security	Investment	Mitigation and adaptation costs	Subsidies	Land use	Pollutions	Resource consumption	Short-termism	Innovative policies	Reformations	Technical standards	Infrastructure
Public engagement	0.00	0.38	0.27	0.15	0.22	0.20	0.49	0.75	0.26	0.52	0.47	0.47	0.39	0.57	0.71	0.56	0.13
Public awareness	0.90	0.00	0.60	0.71	0.43	0.52	0.65	0.59	0.22	0.73	0.86	0.86	0.63	0.48	0.48	0.39	0.39
Public resistance	0.15	0.15	0.00	0.26	0.22	0.15	0.36	0.31	0.31	0.28	0.26	0.26	0.81	0.37	0.13	0.07	0.54
Energy justice	0.88	0.88	0.65	0.00	0.27	0.49	0.33	0.40	0.18	0.20	0.10	0.27	0.71	0.15	0.15	0.33	0.08
Labor transition	0.15	0.08	0.81	0.37	0.00	0.08	0.08	0.25	0.26	0.02	0.02	0.02	0.43	0.20	0.46	0.20	0.02
Energy security	0.58	0.38	0.27	0.58	0.43	0.00	0.77	0.63	0.49	0.18	0.18	0.23	0.39	0.39	0.29	0.39	0.77
Investment	0.90	0.90	0.17	0.90	0.81	0.81	0.00	0.33	0.60	0.71	0.63	0.63	0.86	0.81	0.81	0.81	0.95
Mitigation and adaptation costs	0.73	0.73	0.81	0.62	0.56	0.62	0.62	0.00	0.81	0.59	0.13	0.13	0.67	0.65	0.18	0.18	0.12
Subsidies	0.30	0.30	0.29	0.88	0.49	0.71	0.64	0.73	0.00	0.47	0.47	0.47	0.77	0.55	0.90	0.90	0.56
Land use	0.37	0.20	0.88	0.33	0.26	0.33	0.71	0.49	0.33	0.00	0.84	0.90	0.77	0.22	0.33	0.73	0.67
Pollutions	0.05	0.28	0.90	0.65	0.90	0.86	0.63	0.52	0.31	0.08	0.00	0.31	0.73	0.75	0.90	0.40	0.63
Resource consumption	0.65	0.65	0.49	0.73	0.70	0.73	0.75	0.29	0.29	0.71	0.88	0.00	0.90	0.88	0.64	0.64	0.56
Short-termism	0.90	0.81	0.33	0.73	0.73	0.73	0.67	0.49	0.49	0.58	0.52	0.52	0.00	0.18	0.18	0.65	0.13
Innovative policies	0.81	0.81	0.65	0.77	0.49	0.71	0.77	0.75	0.40	0.40	0.40	0.37	0.37	0.00	0.77	0.58	0.81
Reformations	0.77	0.71	0.67	0.43	0.43	0.49	0.77	0.87	0.65	0.75	0.75	0.75	0.43	0.77	0.00	0.43	0.43
Technical standards	0.65	0.58	0.73	0.49	0.39	0.49	0.49	0.81	0.22	0.62	0.62	0.75	0.75	0.58	0.58	0.00	0.65
Infrastructure	0.77	0.49	0.71	0.77	0.49	0.58	0.65	0.81	0.20	0.65	0.58	0.58	0.58	0.58	0.58	0.58	0.00

Table 6
Features of the cognitive map that have been presented above

Concepts	Outdegree	Indegree	Centrality	Centrality(Normalized)	Centrality(Ranked)
Public engagement	6.55	9.56	16.10	0.056767	11
Public awareness	9.46	8.33	17.79	0.062726	6
Public resistance	4.66	9.22	13.88	0.048929	16
Energy justice	6.07	9.38	15.45	0.054479	15
Labor transition	3.47	7.84	11.31	0.039871	17
Energy security	6.94	8.53	15.47	0.054546	14
Investment	11.63	9.39	21.02	0.074099	1
Mitigation and adaptation costs	8.18	9.03	17.21	0.060665	8
Subsidies	9.44	6.05	15.49	0.054589	13
Land use	8.36	7.51	15.87	0.055948	12
Pollutions	8.93	7.73	16.66	0.058726	10
Resource consumption	10.50	7.54	18.04	0.063581	4
Short-termism	8.68	10.20	18.88	0.066547	2
Innovative policies	9.87	8.13	18.00	0.063453	5
Reformations	10.12	8.10	18.22	0.064216	3
Technical standards	9.41	7.85	17.26	0.060837	7
Infrastructure	9.58	7.45	17.03	0.060021	9

Equation 11, should run to see what values the challenges would get in each iteration. Three developed scenarios are presented below.

Scenario 1: People first

In this scenario, policymakers are assumed to put people at the top of the priorities list. According to this assumption, all indicators closely connected to the public should be fully activated at the first iteration. Thus, I_1 to I_{24} are assigned one. On top of that, it is assumed that due to the high amount of subsidies to support people in this scenario, private companies might be reluctant to invest in the low-carbon energy transition. Thus, all indicators connected to investment are assigned zero, but indicators associated with subsidies are given one. Also, mitigation and adaptation costs might be high due to governmental support in this scenario; thus, all indicators connected to these challenges are assigned zero. It is also assumed that land use is not extreme in this scenario; however, pollution and resource consumption are activated by giving subsidies and support to people, which might increase pollution and resource consumption. Furthermore, short-term solutions are more prevalent when meeting people's expectations is a top priority for policymakers. Also, neither governments nor the private sector has any interest in innovative policies and reformation in this scenario; however, total government budget allocations for R&D are assumed to be activated as it is assumed that governments should always seek long-term solutions even if they currently are seeking short-term solutions. Finally, two indicators connected to the infrastructure are supposed to be activated: transport, telecommunication, and other infrastructures, and the new electricity capacity is bound. The rest are assumed not to be started, as producing energy is not supposed to be high in this scenario.

Scenario 2: Technology first

In this scenario, policymakers are assumed to focus more on the low-carbon energy transition and technological development. According to this assumption, all indicators closely connected to the public are considered partly activated at the first iteration; thus, I_1 to I_{24} are assigned 0.25. However, contrary to the first scenario, private sections are eager to invest in low-carbon energy technologies so that all indicators connected to investment are given one. On top of that, since the main goal is moving toward a low-carbon energy transition, indicators related to GHG reduction, such as GHG-avoided emissions due to renewable energy and Greenhouse gas emissions reductions, GHG Intensity of Energy, and Greenhouse gas intensity of the economy are assumed to be activated. Also, energy productivity is considered to be started as making a profit, which is one of the goals in this scenario. However, subsidies are assumed to be deactivated to make the energy sector more attractive and competitive for the private sector. Land use, pollution, and resource consumption are also considered to be activated as more land might be used to build renewable farms, increasing resource consumption and pollution. Importing energy is not a long-term solution; thus, it is assumed that all indicators connected to imports are deactivated in this scenario. In this scenario, innovative policies and ideas for reformation are welcomed and activated. Also, moving toward a low-carbon energy system requires updated technical standards; thus, it is activated in this scenario. Furthermore, producing low-carbon energy requires new infrastructure; thus, it is activated in this scenario.

Scenario 3: Duet

This scenario compromises priorities. In other words, although technological development should be followed, people should be taken into account in the policymaking process. All indicators connected to the public are assigned 0.5, meaning half-activated. Also, indicators related to investment, mitigation, and adaptation costs are assumed to be half-activated. However, subsidies are considered to be fully activated, influencing public and private sector engagement. On top of that, land use, pollution, and resource consumption are also assumed to be started as policymakers are supposed to seek long-term solutions. On the other hand, short-termism is also considered half-activated since long-term solutions are not the main priority. Innovative policies, reformation, and technical standards are assumed to be fully activated as they require long-term solutions. Finally, investing in infrastructure is also considered half-activated since producing energy is not the main priority. Fig. 1 illustrates the initial values in each scenario.

The first step is to set initial values for each concept in Equation 11 to perform scenario analysis. Once the initial values are set, the model can be run to compute the final values for each concept. The results of the scenario analysis can be found in Table 7. It is worth mentioning that the model reached a steady state after four iterations, indicating that the final values are stable and can be relied upon for further analysis. This information is essential as it provides confidence in the model's accuracy and conclusions.

After analyzing the data, the TOPSIS was utilized to rank the different scenarios based on the final values obtained. The ranking process was based on the data presented in Table 7. Furthermore, to facilitate the TOPSIS analysis, a weighted matrix was used, which is represented in Table 8. The matrix utilized in the ranking process included both Positive Ideal Solution and Negative Ideal Solution values. These values played a crucial role in evaluating and ranking the options available. The Positive Ideal Solution values determined the maximum value each alternative could attain for each criterion. In

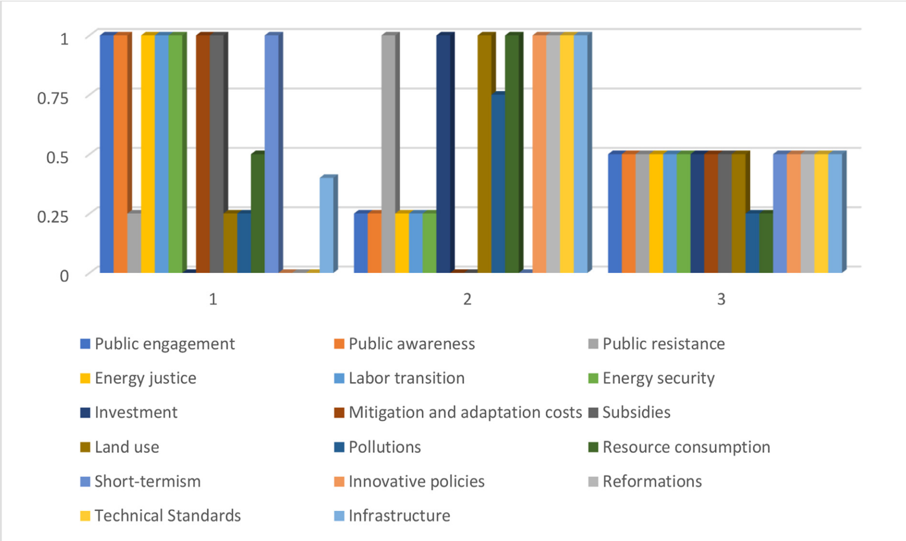

Figure 1. Initial values for running scenarios on FCMapper vs. 1

contrast, the Negative Ideal Solution values were used to determine the minimum value each alternative could attain for each criterion. The comparison of each alternative's performance against these two ideal values helped identify the most suitable option.

The results obtained from the TOPSIS method and the ranking of different scenarios have been presented in Table 9. The table provides a comprehensive overview of the final results obtained from the analysis. It includes the scores of each scenario against the criteria identified and their overall ranking. The TOPSIS method has enabled the evaluation of different scenarios based on multiple criteria, providing a more nuanced understanding of their relative strengths and weaknesses. The presentation of these results in Table 9 should help make informed decisions and identify the most suitable scenario for further action.

Discussion

According to Table 9, the best scenario is the duet, showing that decision-makers must simultaneously consider technological development and people's needs in policymaking; however, meeting people's needs is more crucial in policymaking as the scenario called "people first" ranked second. On top of that, according to Table 6, the most influential concept is "investment," showing that financial investment is a game-changing challenge in developing a low-carbon energy transition. Financial investment in low-carbon technologies is vital for accelerating technological innovation, enabling large-scale deployment, stimulating economic growth, and combating climate change. The development and widespread adoption of low-carbon technologies require substantial funds to overcome technical

Table 7
Results of analying scenarios on FCMapper vs. 1

	SC1					SC2					SC3				
	I0	I1	I2	I3	I4	I0	I1	I2	I3	I4	I0	I1	I2	I3	I4
C1	1	0.999974	0.999974	0.999974	0.999974	0.25	0.933362	0.999947	0.999974	0.999974	0.5	0.994928	0.999973	0.999974	0.999974
C2	1	0.999912	0.999911	0.999911	0.999911	0.25	0.911594	0.999798	0.999911	0.999911	0.5	0.990683	0.999904	0.999911	0.999911
C3	0.25	0.927989	0.999924	0.999964	0.999964	1	0.999964	0.999964	0.999964	0.999964	0.5	0.994014	0.999961	0.999964	0.999964
C4	1	0.999969	0.999969	0.999969	0.999969	0.25	0.930562	0.999936	0.999969	0.999969	0.5	0.994463	0.999967	0.999969	0.999969
C5	1	0.999856	0.999855	0.999855	0.999855	0.25	0.901203	0.999654	0.999855	0.999855	0.5	0.988125	0.99984	0.999855	0.999855
C6	1	0.999927	0.999927	0.999927	0.999927	0.25	0.915511	0.999838	0.999927	0.999927	0.5	0.991555	0.999921	0.999927	0.999927
C7	0	0.5	0.994491	0.999968	0.999969	1	0.999969	0.999969	0.999969	0.999969	0.5	0.994491	0.999968	0.999969	0.999969
C8	1	0.999956	0.999956	0.999956	0.999956	0	0.5	0.993416	0.999953	0.999956	0.5	0.993416	0.999953	0.999956	0.999956
C9	1	0.999131	0.999126	0.999126	0.999126	0	0.5	0.971357	0.998937	0.999125	0.5	0.971357	0.998937	0.999125	0.999126
C10	0.25	0.893481	0.9995	0.999797	0.999798	1	0.999798	0.999798	0.999798	0.999798	0.5	0.985986	0.999772	0.999798	0.999798
C11	0.25	0.898617	0.999608	0.999837	0.999838	0.75	0.998566	0.999836	0.999838	0.999838	0.25	0.898617	0.999608	0.999837	0.999838
C12	0.5	0.986196	0.99978	0.999804	0.999804	1	0.999804	0.999804	0.999804	0.999804	0.25	0.894206	0.999517	0.999803	0.999804
C13	1	0.999986	0.999986	0.999986	0.999986	0	0.5	0.996312	0.999986	0.999986	0.5	0.996312	0.999986	0.999986	0.999986
C14	0	0.5	0.989693	0.999881	0.999891	1	0.999892	0.999891	0.999891	0.999891	0.5	0.989693	0.999881	0.999891	0.999891
C15	0	0.5	0.989519	0.999877	0.999888	1	0.999888	0.999888	0.999888	0.999888	0.5	0.989519	0.999877	0.999888	0.999888
C16	0	0.5	0.988163	0.999841	0.999856	1	0.999857	0.999856	0.999856	0.999856	0.5	0.988163	0.999841	0.999856	0.999856
C17	0.4	0.967043	0.999717	0.999785	0.999785	1	0.999786	0.999785	0.999785	0.999785	0.5	0.985569	0.999758	0.999785	0.999785

Table 8
Weighted matrix, PIS, and NIS

	SC1	SC2	SC3	S+	S-
Public engagement	0.032774278	0.032774278	0.032774278	0.032774278	0.032774278
Public awareness	0.036215015	0.036215015	0.036215015	0.036215015	0.036215015
Public resistance	0.028249306	0.028249306	0.028249306	0.028249306	0.028249306
Energy justice	0.031453513	0.031453513	0.031453513	0.031453513	0.031453513
Labor transition	0.023019395	0.023019395	0.023019395	0.023019395	0.023019395
Energy security	0.031492152	0.031492152	0.031492152	0.031492152	0.031492152
Investment	0.042780836	0.042780836	0.042780836	0.042780836	0.042780836
Mitigation and adaptation costs	0.035024811	0.035024811	0.035024811	0.035024811	0.035024811
Subsidies	0.031517161	0.031517124	0.03151716	0.031517161	0.031517124
Land use	0.032301868	0.032301868	0.032301868	0.032301868	0.032301868
Pollutions	0.033905491	0.033905491	0.033905491	0.033905491	0.033905491
Resource consumption	0.03670831	0.03670831	0.03670831	0.03670831	0.03670831
Short-termism	0.038421015	0.038421015	0.038421015	0.038421015	0.038421015
Innovative policies	0.036634752	0.036634752	0.036634752	0.036634752	0.036634752
Reformations	0.037074904	0.037074905	0.037074905	0.037074905	0.037074904
Technical Standards	0.035124442	0.035124442	0.035124442	0.035124442	0.035124442
Infrastructure	0.034653031	0.034653031	0.034653031	0.034653031	0.034653031

Table 9
TOPSIS results and scenarios rank

	S_i^+	S_i^-	C_i^*	Rank
SC1	9.04022E-10	3.66708E-08	0.975940764	2
SC2	3.66708E-08	9.03616E-10	0.024048668	3
SC3	2.31903E-10	3.64562E-08	0.993679071	1

challenges, bridge cost gaps, and create the necessary infrastructure. These results are in line with McCauley et al. (2019) and Siciliano et al. (2021) studies in which they mentioned that a transition to a low-carbon economy requires a comprehensive perspective on the interaction between people, the environment, and the economy, in which community opinions are addressed in policy processes.

On top of that, "short-termism" ranked as the second most influential challenge in the case of Lithuania. Long-term strategies play a crucial role; however, short-term policies are also vital in transitioning to a low-carbon economy. For instance, implementing short-term policies like carbon pricing could deliver economic incentives for reducing greenhouse gas emissions. Carbon pricing can boost productivity, increase energy efficiency, and support the low-carbon energy transition (Pradhan & Ghosh, 2022). Also, short-term policies emphasizing public awareness and education programs are essential for promoting behavioral changes and sustainable practices. Information dissemination, general discussions, and educational initiatives can raise knowledge of the advantages of low-carbon energy and the need to reduce emissions (Baek et al., 2019). By enabling people, communities, and businesses with information, these policies stimulate demand for low-carbon systems, changes in consumer behavior, and their resistance to change, the main challenges to "reformation," ranked as the third most influential challenge (Huang, 2021).

Scenarios are a valuable tool for describing events and situations that might occur in the future. The proposed approach takes a unique perspective in that it aims to use scenarios that are built, assessed, and ranked as a whole. Unlike traditional approaches, which consider the future impact of each present entity in isolation, this approach recognizes the complex reality in which different entities interact with each other. Considering the interactions between different entities, this approach can provide a more nuanced and detailed understanding of potential future scenarios. Overall, this approach offers a more comprehensive way of thinking about the future that can be especially useful in complex and uncertain situations.

Conclusions and policy implications

The present study applied an intuitionistic fuzzy cognitive map to analyze the low-carbon energy transition in the case of Lithuania under three different scenarios. Subsequently, the TOPSIS method was used to rank scenarios and determine which developed scenarios are the best to apply according to three experts' opinions. According to the obtained results, it could be concluded that the transition to a low-carbon energy system requires active participation and engagement from all levels of society. Individuals, communities, and organizations play indispensable roles in shaping consumption patterns, fostering community engagement, advocating for supportive policies, driving innovation and entrepreneurship, and shaping social norms and culture. The collective efforts of society are crucial in accelerating the adoption of renewables and mitigating the impacts of climate change. Also, it could be concluded that advancements in renewable energy integration, energy storage, energy efficiency, electrification, and carbon capture technologies are critical in reducing greenhouse gas emissions and promoting sustainable development. Governments, research institutions, and private industries must continue to invest in research and development, foster innovation, and create an enabling environment for technology deployment. Therefore, the following policies could be implemented in Lithuania to move toward a low-carbon energy transition system:

- Renewable energy support mechanisms:

Implement feed-in tariffs, power purchase agreements (PPAs), or auction schemes to incentivize the development of renewable energy sources. These mechanisms can ensure long-term contracts and stable prices for renewable energy producers, stimulating investment in wind, solar, biomass, and hydropower projects. Additionally, a clear regulatory framework for community-owned renewable energy projects should be established to encourage local participation and enhance energy self-sufficiency.

- Energy efficiency programs:

Introduce energy efficiency programs targeting buildings, industries, and transportation. Provide financial incentives, grants, and low-interest loans to encourage energy-efficient building retrofits, appliance upgrades, and the adoption of energy-efficient technologies. Implement energy performance standards and labeling requirements to promote energy-efficient products. Raise public awareness through educational campaigns to encourage behavior change and energy-saving practices.

- Carbon pricing and emissions trading:

Implement a carbon pricing mechanism, such as a carbon tax or emissions trading system, to put a price on carbon emissions. This approach incentivizes industries to reduce greenhouse gas emissions and invest in low-carbon technologies. Revenue generated from carbon pricing can be reinvested in renewable energy projects, energy efficiency initiatives, and research and development in clean technologies.

- Sustainable transportation initiatives:

Encourage the adoption of electric vehicles (EVs) by implementing policies such as financial incentives, tax exemptions, and the development of EV charging infrastructure. Support the expansion of public transportation networks, including electric buses and trains. Promote cycling and walking infrastructure to reduce the reliance on private vehicles. Encourage using alternative fuels, such as biofuels or hydrogen, in transportation.

- Grid modernization and flexibility:

Invest in grid modernization to enhance the integration of renewable energy sources and improve grid flexibility. Upgrade transmission and distribution infrastructure to accommodate decentralized energy generation and bi-directional power flow. Implement innovative grid technologies, advanced metering systems, and demand response programs to optimize energy use and manage peak demand. Facilitate the development of energy storage systems to ensure grid stability and support intermittent renewable energy sources.

- Research and innovation support:

Allocate funding for research and innovation in low-carbon technologies and clean energy solutions. Support partnerships between research institutions, universities, and private sectors to promote technology development and commercialization. Provide grants, tax incentives, and support for startups and businesses focused on developing and scaling up innovative low-carbon technologies.

- International collaboration:

Engage in knowledge sharing and international collaboration to learn from other countries' best experiences and practices in transitioning to a low-carbon energy system. Participate in regional and global initiatives, such as the European Union's Clean Energy Package and the Paris Agreement, to align national efforts with international climate goals and benefit from financial and technical support.

To sum up, it is crucial to continuously monitor and evaluate the effectiveness of implemented policies and adjust them as needed to ensure progress toward a low-carbon energy system. Regular stakeholder consultations, public engagement, and transparency in policy decision-making are essential for building consensus and maintaining momentum in the transition to a sustainable and low-carbon energy future in Lithuania.

Research limitations and future directions

Data collection and drawing individual maps using FCM was time-consuming since experts were unfamiliar with the method. Importing developed scenarios on FCMapper was also a time-consuming and complex task. Furthermore, applying multicriteria decision-making methods to find places for building energy farms in Lithuania, using the present study's method in other countries, and comparing the results with the current study could be some recommendations for future studies.

CRediT authorship contribution statement

Mahyar Kamali Saraji: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Dalia Streimikiene:** Conceptualization, Investigation, Project administration, Resources, Supervision, Writing – review & editing.

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A novel two-stage multicriteria decision-making approach for selecting solar farm sites: A case study

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ABSTRACT

The Baltic region relies heavily on imported fossil fuels and strongly emphasizes renewable energy development. However, certain obstacles, such as site selection, hinder solar energy development in this region. Therefore, major energy stakeholders must identify optimal solar photovoltaic construction locations. The present study endeavored to conduct a comprehensive and meticulous review of pertinent literature published from 2013 to 2023 to identify critical factors that influence site selection and look into various methodologies employed in this domain. Later, a two-stage approach was used for the first time to identify the most suitable locations among 39 potential cities in the Baltic region for constructing solar PV farms. In the first stage, Data envelopment analysis (DEA) models were used to filter out the areas with the highest potential by measuring their efficiency indices using temperature, wind speed, humidity, precipitation, and air pressure as inputs and sunshine hours, elevation, and irradiation as outputs. Subsequently, six selected evaluation criteria were used to prioritize the locations with solar energy potential. In the second stage, CRiteria Importance Through Intercriteria Correlation (CRITIC)-Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was used to determine the criteria's objective weights and rank potential sites for the research case study. The results indicate that 25 locations in the Baltic region are suitable for building solar farms, with specific photovoltaic power output being the most significant criterion that impacts solar site selection. Furthermore, by excluding Gross domestic product (GDP) and labor force from the analysis, the results can align with the Global Solar Atlas's reports.

1. Introduction

Solar energy is progressively gaining momentum as a viable option for developing Baltic countries like Lithuania, transitioning from traditional fossil fuels to more sustainable, cost-effective, and environmentally friendly energy sources (Kuşkaya et al., 2023; Kasradze et al., 2023). The shift holds immense significance for the country's long-term economic and environmental prosperity, and solar energy is a promising solution to achieve these objectives (Li et al., 2023; Saraji and Streimikiene, 2023). By capitalizing on the sun's energy, Lithuania can diminish its reliance on non-renewable energy sources, diminish its carbon footprint, and pave the way for a more sustainable future for future generations (Gaigalis and Katinas, 2020). On top of that, due to advancements in technology and mass production, the decreasing cost of photovoltaic modules has resulted in a 25% reduction with every doubling of production (Khan et al., 2023). The cost reduction has made solar power increasingly cost-competitive in numerous regions and is projected to do so in others shortly, despite the steady prices of conventionally produced electricity (Kumar et al., 2023). While there are uncertainties regarding the future, such as political willingness, societal acceptance, and energy system expenses, studies demonstrate that 100% renewable energy will be feasible worldwide by 2050 at reasonable electricity costs (Tan et al., 2023; Saraji and Streimikiene, 2023). However, the models and scenarios predicting the deployment of solar energy by 2050 differ significantly. Researchers argue that despite its numerous advantages, the potential of solar energy deserves greater recognition (Spyridonidou and Vagiona, 2023).

Furthermore, over the last two decades, Lithuania, a small nation in Europe's Baltic region, has undergone a series of substantial energy transitions. Following the closure of its single nuclear power plant, Ignalina, Lithuania, shifted from being a net exporter of electricity to a net importer (Štreimikienė et al., 2022). Lithuania imports approximately 9 TWh of electricity annually to accommodate an average annual consumption of roughly 11 TWh. Before April 2022, Lithuania's primary source of natural gas was acquired via import from neighboring Russia,

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Nomenclature

DEA models

n	Number of DMUs
m	Number of inputs
q	Number of outputs
ν_r	The weight of r_{th} input
x_{ik}	The inputs of K_{th} DMU
u_r	The weight of r_{th} output
y_{rk}	The outputs of k_{th} DMU

CRITIC-TOPSIS

x_{ij}	The given value to the i_{th} site according to the j_{th} criteria
$\overline{x}_{ij}$	The normalized given value to the i_{th} site according to the j_{th} criteria
x_j^-	The minimum amount of $\overline{x}_{ij}$
x_j^+	The maximum amount of $\overline{x}_{ij}$
σ_j	The standard deviation for the jth criterion
r_{jt}	the correlation between the jth and the t_{th} values
ν_j	The information quantity for the jth criterion
ϖ_j	The weight of the jth criterion
$\widehat{x}_{ij}$	The weighted given value to the i_{th} site according to the j_{th} criteria
A^+	Positive ideal solutions sets
A^-	Negative ideal solutions sets
S_i^+	The separation measure for the ith alternative in the positive direction
S_i^-	The separation measure for the ith alternative in the negative direction
C_i^*	The relative closeness for the ith alternative

resulting in significant energy dependency (Sattich et al., 2022). Furthermore, Lithuania was considered part of the Baltic energy island due to its unique position within the regional energy system. Given its limited fossil energy resources, this area is widely acknowledged as vulnerable to dominance by a singular supplier (Kozlovas et al., 2023). In this context, Lithuania has taken a proactive approach to ensuring energy security, recognizing the importance of reducing dependence on imports given the geopolitical tensions in the region (Jonek-Kowalska, 2022). Lithuania's energy sector has been developed to increase self-sufficiency and reduce import dependency. Although renewable energy sources are considered crucial for enhancing energy security, adopting such sources has been slower than anticipated in Lithuania (Lisauskas et al., 2022). This situation may be attributed to various factors, such as the implementation costs of renewable energy infrastructure and the need for a reliable energy grid to support these sources (Tumelienė et al., 2022). Nevertheless, if Lithuania can overcome these challenges, the country has the potential to become a leader in renewable energy adoption in the Baltic region, further strengthening its energy security position (Lisauskas et al., 2022).

Adopting photovoltaic solar panels has significant environmental consequences, varying in severity based on location (Romero-Ramos et al., 2023; Saraji et al., 2023). For instance, land acquisition plays a crucial role in promoting the adoption of solar energy. Project developers must negotiate with landowners along the transmission route, either acquiring or renting the land and compensating landowners accordingly (Coruhlu et al., 2022). In this context, identifying appropriate locations for constructing these solar farms is an essential strategic decision for promoting their uptake. However, this decision-making process can be challenging for businesses, stakeholders, and policymakers due to the region's combination of economic and technical perspectives and sustainable aspects for further solar power development. Therefore, researchers have conducted research in which models are developed for selecting solar farm sites. For instance, Wang et al. (2023a) applied an integrated Data Envelopment Analysis (DEA)-fuzzy multicriteria decision-making (MCDM) model to assess the potential sites for constructing solar farms in Indonesia, Wang et al. (2022a) applied a combined DEA and Grey MCDM model for solar PV power plants' site selection in Vietnam, Wang et al. (2021a) applied a hybrid evaluation model by integrating DEA with the Analytic Hierarchy Process (AHP) to select the best solar farm location among 20 potential locations in Taiwan.

According to the literature, see Section 2, most studies conducted to develop evaluation methods for site selection have utilized GIS tools, which rely on environmental and climate data. While these factors are undoubtedly important, many other social, economic, and technical factors can significantly impact selecting a solar farm site. For instance, considerations such as labor market conditions and Gross domestic product (GDP) can play a crucial role in determining optimal locations for solar farms. Given the complex interplay of these various factors, the present research aims to provide a comprehensive framework for evaluating all the relevant factors that can impact solar farm site selection. Also, most research used AHP to determine the weights of factors and rank alternatives in the second stage of site evaluation. However, it heavily relies on subjective pairwise comparisons, making it sensitive to the decision-maker's judgment and prone to inconsistency issues, potentially leading to unreliable rankings. Constructing a hierarchy, conducting these comparisons, and deriving criteria weights can be complex, time-consuming, and challenging to manage, particularly in decision problems involving many criteria and alternatives. AHP's results can be challenging to interpret and communicate, especially in complex scenarios, and it may require considerable expertise and resources. Additionally, the method's transparency and ease of use can be compromised, and it may perform poorly in cases with missing or incomplete data, making it less versatile in real-world decision-making situations. Therefore, the present study used the CRiteria Importance Through Inter-criteria Correlation (CRITIC)-Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)method to overcome the mentioned shortcomings of AHP.

The CRITIC method offers several benefits over the AHP when determining criteria weights. It demonstrates greater resilience to changes in pairwise comparisons, resulting in more consistent outcomes. It also handles inconsistencies in comparisons and recognizes correlations between criteria, making it more straightforward to implement and accommodate various data types without complex transformations. These features make CRITIC a more transparent, user-friendly, and adaptable approach to determining criteria weights, which is especially useful when decision-makers require reliable and intuitive results in complex multicriteria decision-making scenarios. Moreover, TOPSIS presents significant benefits compared to AHP regarding ranking alternatives. Its implementation is more straightforward, requiring fewer complex steps, like constructing hierarchies or conducting extensive pairwise comparisons. The results are intuitive and straightforward, based on the proximity of alternatives to ideal solutions, facilitating interpretation and communication. Additionally, TOPSIS is less sensitive to subjectivity and inconsistencies in judgments, making it a more robust and objective method. It is an excellent choice for decision-makers who want a transparent and efficient approach to ranking alternatives without extensive data manipulation, making it a practical solution for various decision-making scenarios.

On the other hand, the literature reveals that no study regarding sustainable development has thoroughly investigated solar site selection in Baltic regions, especially Lithuania. The authors believe this research is a practical step to attain benefits from solar energy and contribute to the spread of their implementation in Baltic regions. This study aims to determine the best locations for solar PV development in the Baltic region, with a particular focus on Lithuania, to promote sustainability. After reviewing relevant literature and consulting with experts, potential locations and criteria that impact solar deployment were identified. Because multiple factors must be considered in making this decision, the study utilized MultiCriteria Decision-Making (MCDM) methodologies. A two-stage framework integrates DEA, CRITIC, and TOPSIS to evaluate and rank potential locations suitable for solar-powered production. The main contributions of the present article are presented in the following:

1. To identify environmental, economic, social, and technical factors impacting solar farm selection in Baltic regions. Considering these factors leads to the development of sustainable and successful renewable energy projects that contribute to environmental protection, economic growth, social well-being, and technological advancement.
2. To propose a novel integrated model by integrating DEA and MCDM models for solar farm site selection. The advantages of the integrated method include a comprehensive evaluation, balanced decision-making, objective efficiency assessment, flexibility in criteria incorporation, transparency, robustness analysis, and improved resource allocation. The model leads to more well-informed, sustainable, and effective decisions in building solar farms.
3. To apply the proposed integrated model to a case study. The integrated model simulates a realistic decision scenario where various factors are considered simultaneously, mimicking the complexity of real-world decision-making processes.

The article's structure is as follows: Section 2 reviews methods for selecting solar farm sites. Section 3 presents the research methods. Results are presented in Section 4. Sensitivity analysis is presented in Section 5. Discussion is presented in Section 6. Section 7 provides broad conclusions on obtained results, and policy implementations are also provided in Section 7.

2. A review of applied methods for solar farm site selection

In this section, a systematic literature review is conducted to review articles published from 2013 to 2023 in which models and methods were applied to select suitable sites for building solar farms. Articles must meet the following criteria: the search keywords should appear in the title, abstract, or keywords, and the article must be published in a peer-reviewed scientific journal. However, the following articles will be excluded: editorial letters, chapter books, review papers, academic theses, conference proceedings, duplicated publications, and studies written in languages other than English. The following research strings have been used to find articles indexed on Scopus and Web of Science over the last decade:

TITLE-ABS-KEY: ("Site selection" OR "Location selection" OR "Location choices" OR "Site evaluation" OR "Site assessment" OR "Site suitability") AND ("Solar power" OR "Solar energy" OR "Solar farm" OR "Solar plant")).

According to the reviewed articles, most studies applied Geographic information science (GIS) to deal with site selection problems. GIS is a versatile tool with many applications ranging from urban planning and natural resource management to disaster management and navigation apps. Its ability to facilitate decision-making processes and analyze spatial relationships and patterns across industries makes it a valuable asset in various academic disciplines. However, GIS was usually integrated with multicriteria decision methods, especially the Analytical Hierarchical Process (AHP). AHP is a decision-making method that involves several crucial steps. First, it establishes a hierarchical structure for the decision problem by breaking it down into goals, criteria, subcriteria, and alternatives. Next, by assigning numerical values, decision-makers compare each element pairwise to determine their relative importance or preference within each hierarchy level. These values are then used in mathematical calculations to derive priority scores for criteria and alternatives. A consistency check ensures the reliability of the judgments. Finally, the method aggregates the priority scores to identify the best alternative or decision, promoting systematic and rational decision-making, especially in situations with multiple criteria and trade-offs.

For instance, Raza et al. (2023) applied a combination of GIS- AHP to find suitable sites for wind and solar farms. They included solar irradiation, average temperature, land cover, slope, land aspects, proximity to urban areas, roads, and power lines as factors impacting solar and wind farm selection. The developed methodology was utilized in a study of Pakistan, a developing country experiencing a severe climate change crisis and an ongoing power shortage. Also, Kocabaldır and Yücel (2023) applied the GIS-AHP method for spatial planning of solar photovoltaic power plants in Turkey. They included solar irradiation, average temperature, land cover, slope, land aspects, proximity to urban areas, roads, and power lines as factors impacting solar and photovoltaic power plants. The most appropriate sites demonstrated the potential to meet all the electrical energy requirements of the province of Çanakkale during the installation, and Tafula et al. (2023) applied GIS-AHP for optimum site selection for off-grid solar photovoltaic Microgrids in Mozambique. They included humidity, temperature, pressure, sunshine hour, slope, irradiation, land use, elevation, distance from roads, job opportunities, energy justice, and human development index as factors impacting off-grid solar photovoltaic microgrids. The methodology has revealed that determining the best sites for off-grid solar photovoltaic microgrid initiatives in Mozambique depends mainly on the following priorities: climatic conditions, topography, technical and geographical location, social aspects, and institutional factors. Appendix 1 summarizes research in which an integrated GIS-AHP method was used for site selection.

Moreover, specific research endeavors have employed GIS either independently or in conjunction with other methodologies, such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS, The analytic network process (ANP), Full consistency method (FUCOM), Best-Worst Method (BWM). For instance, Hasti et al. (2023) integrated MCDM methods with GIS to find the optimal solar photovoltaic sites in Kurdistan and assess environmental and economic impacts. They included meteorology, topology, shape of the earth, Human infrastructure, and supplementary criteria as factors impacting solar photovoltaic site selection. The outcomes can inform policy and investment strategies for renewable energy development in regions with comparable environmental and economic conditions. Also, Uyan and Dogmus (2023) applied an integrated GIS-based ANP analysis to select solar farm installation locations in Turkey. They included aspects such as distance from transmission lines, distance from surface waters, distance from transformer centers, distance from residential areas, and distance from roads and railways as factors impacting solar farm installation locations. The suitability map was divided using an equidistant classification method into three categories: low, moderate, and high suitability, and Khan et al. (2023) used an integrated GIS-FUCOM model to select solar PV power plant sites in Pakistan. They included solar radiation, aspect, temperature, land use, distance to road, residential areas, and transmission lines as factors impacting solar PV power plant selection. The outcomes showcase the distribution of appropriate locations to build solar photovoltaic power stations nationwide. Appendix 2 summarizes research in which GIS was applied independently or in conjunction with different techniques.

Furthermore, some studies applied other methods, such as Stepwise Weight Assessment Ratio Analysis (SWARA), Weighted aggregated sum product assessment (WASPAS), Delphi, machine learning, genetic algorithm, VIekriterijumsko KOmpromisno Rangiranje (VIKOR), Measurement of Alternatives, and Ranking according to the Compromise Solution (MARCOS), and The CRiteria Importance Through Intercriteria

Correlation (CRITIC) to select suitable places for building solar farms. For instance, Ahadi et al. (2023) used AHP to select optimal sites for solar power plants in Iran. They included solar radiation, sunny days, temperature, humidity, rainfall, air pollution, and cloudiness as factors impacting solar power plant selection. Results indicated that Zahedan has been identified as the ideal site for establishing a solar power facility after analyzing the provincial hubs of Iran. Also, Qasimi et al. (2023) used genetic algorithms to select optimal solar PV sites in northern Afghanistan. They included irradiation, slope, elevation, temperature, proximity to transmission lines, residential areas, roads, and aspects impacting solar PV selection. In northern Afghanistan, the genetic algorithm demonstrated better performance than AHP. It could accurately identify more than 29,000 square kilometers of land suitable for installing solar power plants, and Mian et al. (2023) used mechanisms for choosing PV locations to have the most sustainable usage of solar energy. They included solar radiation, GHI, wind speed, sunshine hours, topography, population, and sand and dust storms as factors impacting solar PV plants. Based on the analysis, it has been determined that solar radiation and sunshine hours are the most critical factors when selecting PV sites. Furthermore, it has been inferred that Tabuk is the best location for building a solar power plant out of all the cities surveyed. Appendix 3 summarizes the application of the method for determining solar farm sites.

According to the reviewed literature, no study has been conducted regarding site selection for solar farms in the Baltic region. Additionally, no research has employed the integrated DEA-CRITIC-TOPSIS methodology to select solar farm sites. Hence, the current study is unique and innovative, not only in terms of the case study location but also due to its research methodology.

3. Research method

3.1. Data Envelopment Analysis (DEA)

A quantitative technique known as Data Envelopment Analysis is used in operations research and management science to assess the relative efficiency of decision-making units (DMUs), which can include individuals, organizations, and companies. Typically, DEA is employed to gauge the effectiveness and efficiency of numerous DMUs with multiple inputs and outputs. DEA is a non-parametric method that does not rely on assumptions regarding the functional form of the production process or the error distribution. The DEA must identify both the input and output variables. The input variables refer to the resources and factors utilized in a process, whereas the output variables represent the outcomes or products of the process. It is critical to carefully choose these variables to ensure they accurately reflect the unique characteristics of the DMUs being evaluated. Each DMU's input and output variables are recorded, usually in a matrix format. The matrix has one row per DMU and columns representing the input and output variables. DEA computes efficiency scores for each DMU, indicating how efficiently they utilize their inputs to produce outputs. An efficiency score of 1 implies that the DMU is fully efficient, while a score less than 1 suggests inefficiency. The weights allocated to inputs and outputs can assist in recognizing the causes of inefficiency, allowing managerial decisions to be made to optimize operations. There are two standard DEA models: (1) the CCR (Charnes–Cooper–Rhodes) DEA model(a model of constant returns to scale) and (2) the BCC (Banker–Charnes–Cooper) DEA model (a model of variable returns of scale). These two models are presented for both input and output-oriented forms by Eqs. (1)–(4) (Zhang and Li, 2020; Cattani, 2023):

Let $DMU_j = (j = 1, \ldots, n)$ a set of decision-making units, $(x_{1j}, \ldots, x_{mj})$ an input vector of DMU_j with the input weight vector $(\nu_1, \ldots, \nu_m)$, and $(y_{1j}, \ldots, y_{qj})$ an output vector of DMU_j with the output weight vector $(u_1, \ldots, u_q)$. Assume that each DMU_j consumes x_{ij} amount of input i to produce y_{ij} amount of output r. $(x_{1j}, \ldots, x_{mk})$ and $(y_{1j}, \ldots, y_{qk})$ are the input and output of $DMU_k = (j = 1, \ldots, n)$; where x_{ik} and $y_{ik} \geq 0$. Let $\mu_r = tu_r$ and $\nu_i = t\nu_i$, where $t = \left(\sum_{i=1}^{m} \nu_i x_{ik}\right)^{-1}$.

- Input-oriented CCR DEA model

$$Max \frac{\sum_{r=1}^{q} u_r y_{rk}}{\sum_{i=1}^{m} \nu_r x_{ik}}$$

$$\text{Subject to}: \tag{1}$$

$$\begin{cases} \dfrac{\sum_{r=1}^{q} u_r y_{rk}}{\sum_{i=1}^{m} \nu_r x_{ik}} \leq 1 \ (j = 1, .., n) \\ u_r \geq 0 \ (r = 1, .., q); \ \nu_i \geq 0 \ (i = 1, \ldots, m) \end{cases}$$

- Input-oriented BCC DEA model

$$Max \sum_{r=1}^{q} \mu_r y_{rk} + \mu_0$$

$$\text{Subject to}: \tag{2}$$

$$\begin{cases} \sum_{r=1}^{q} \mu_r y_{rk} - \sum_{i=1}^{m} \nu_r x_{ij} + \mu_0 \leq 0 \ (j = 1, .., n), \sum_{i=1}^{m} \nu_i x_{ik} = 1 \\ \mu_r \geq 0 \ (r = 1, .., q); \ \nu_i \geq 0 \ (i = 1, \ldots, m), \mu_0 \in R \end{cases}$$

- Output-oriented CCR DEA model

$$Min \frac{\sum_{i=1}^{m} \nu_r x_{ik}}{\sum_{r=1}^{q} u_r y_{rk}}$$

$$\text{Subject to}: \tag{3}$$

$$\begin{cases} \dfrac{\sum_{i=1}^{m} \nu_r x_{ik}}{\sum_{r=1}^{q} u_r y_{rk}} \geq 1 \ (j = 1, .., n) \\ u_r \geq 0 \ (r = 1, .., q); \ \nu_i \geq 0 \ (i = 1, \ldots, m) \end{cases}$$

- Output-oriented BCC DEA model

$$Max \sum_{i=1}^{m} \nu_r x_{ik} + \nu_0$$

$$\text{Subject to}: \tag{4}$$

$$\begin{cases} \sum_{r=1}^{q} \mu_r y_{rk} - \sum_{i=1}^{m} \nu_r x_{ij} + \nu_0 \leq 0 \ (j = 1, .., n), \sum_{r=1}^{q} \mu_r y_{rk} = 1 \\ \mu_r \geq 0 \ (r = 1, .., q); \ \nu_i \geq 0 \ (i = 1, \ldots, m), \nu_0 \in R \end{cases}$$

3.2. CRITIC-TOPSIS

Step 1 (Hassan et al., 2023a; Saraji et al., 2021). Decision matrix constructing

Consider a set of potential sites denoted by $\{c_1, c_2, \ldots, c_m\}$, and a set of criteria denoted by $\{I_1, I_2, \ldots, I_n\}$; thus, $\mathbb{Z} = (x_{ij})_{m \times n}$. Let $x_{ij}\ \forall\ i = 1, \ldots, m$; $j = 1, \ldots, n$ represent the given value to the $\mathrm{i_{th}}$ site according to the $\mathrm{j_{th}}$ criteria.

Step 2 Normalization

The normalization process of matrix $\mathbb{N} = (\overline{x}_{ij})_{m\times n}$ will be executed using Eq. (5), with the assistance of $x_j^- = \min_i x_{ij}$ and $x_j^+ = \max_i x_{ij}$.

$$\overline{x}_{ij} = \begin{cases} \dfrac{x_{ij} - x_j^-}{x_j^+ - x_j^-}, j \in N_b \\ \dfrac{x_j^+ - x_{ij}}{x_j^+ - x_j^-}, j \in N_n \end{cases} \quad (5)$$

Step 3 Standard deviation

The calculation of the standard deviation (σ_j) can be derived through the utilization of Eq. (6), where $\overline{x}_j = \sum_{i=1}^{m} \frac{\overline{x}_{ij}}{m}$.

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{m} \left(\overline{x}_{ij} - \overline{x}_j\right)^2}{m}} \quad (6)$$

Step 4 Correlation

The calculation of the correlation (r_{jt}) can be derived through the utilization of Eq. (7).

$$r_{jt} = \frac{\sum_{i=1}^{m} \left(\overline{x}_{ij} - \overline{x}_j\right)\left(\overline{x}_{it} - \overline{x}_t\right)}{\sqrt{\sum_{i=1}^{m} \left(\overline{x}_{ij} - \overline{k}_j\right)^2 \sum_{i=1}^{m} \left(\overline{x}_{it} - \overline{x}_t\right)^2}} \quad (7)$$

Step 5 Information quantity

The calculation of the information quantity (ν_j).can be derived through the utilization of Eq. (8)

$$\nu_j = \sigma_j \left(\sum_{t=1}^{n} (1 - r_{jt}) \right) \quad (8)$$

Step 6 Final weights

Eq. (9) calculates the final weights (ϖ_j).

$$\varpi_j = \frac{\nu_j}{\sum_{i=1}^{m} \nu_j} \quad (9)$$

Step 7 Weighted matrix

The calculation of the weighted matrix is achieved through the utilization of Eq. (10), subject to $\sum_{i=1}^{n} \varpi_j = 1$.

$$\widehat{x}_{ij} = \overline{x}_{ij} * \varpi_j \ (i = 1, \ldots, m; j = 1, \ldots., n) \quad (10)$$

Step 8 Positive and negative ideal solutions

Eqs. (11) and (12) are utilized for the computation of both positive and negative ideal solutions.

$$A^+ = \left\{ \left(\max_i \widehat{x}_{ij} | j \in J \right), \left(\min_i \widehat{x}_{ij} | j \in \acute{J} \right) | \, i = 1, \ldots, m \right\} = \left\{ x_1^+, x_2^+, \ldots, x_n^+ \right\} \quad (11)$$

$$A^- = \left\{ \left(\min_i \widehat{x}_{ij} | j \in J \right), \left(\max_i \widehat{x}_{ij} | j \in \acute{J} \right) | \, i = 1, \ldots, m \right\} = = \left\{ x_1^-, x_2^-, \ldots, x_n^- \right\} \quad (12)$$

Where $J = \{j = 1, 2, \ldots, n | j \textit{ associated with the benefit criteria}\}$, and $\acute{J} = \{j = 1, 2, \ldots, n | j \textit{ associated with the cost criteria}\}$.

Step 9 The separation measures

Eqs. (13) and (14) can be utilized to determine the optimal separation, both in the positive and negative directions.

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(\widehat{x}_{ij} - x_j^+\right)^2} \ (i = 1, \ldots, m) \quad (13)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(\widehat{x}_{ij} - x_j^-\right)^2} \ (i = 1, \ldots, m) \quad (14)$$

Step 9 Relative closeness calculation

The calculation for determining relative closeness is derived from Eq. (15).

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^+}, 0 < C_i^* < 1, i = 1, \ldots, m \quad (15)$$

Where $C_i^* = 1 \textit{ if } A_i = A^+$, and $C_i^* = 0 \textit{ if } A_i = A^-$. The sites have been arranged in descending order based on their respective C_i^*. Fig. 1 illustrates the research stages.

4. A case study in the Baltic

Lithuania's location in the Baltic region of northern Europe can significantly impact the solar irradiance it receives throughout the year. Due to its high latitude, the sun's angle changes quite dramatically throughout the seasons, resulting in distinct seasonal fluctuations in solar irradiance. The average solar irradiance in Lithuania varies throughout the year due to its high latitude and changing seasons. On an annual basis, Lithuania receives an average solar irradiance of around 1000 to 1100 kWh/m^2 (kilowatt-hours per square meter). More specifically, Lithuania experiences its highest solar irradiance levels during summer. Solar irradiance can reach around 1300 to 1400 kWh/m^2 during this period.

Furthermore, solar irradiance is somewhat lower during the transitional seasons in spring and fall, ranging from 1000 to 1200 kWh/m^2. Also, Winter months have the lowest solar irradiance, dropping to around 600 to 700 kWh/m^2. The shorter daylight hours and lower sun angles reduce solar energy production during this time. This section showcases the successful implementation of a recommended collective framework. The framework was utilized to evaluate the 39 nominated locations in the Baltic region to establish solar power plants. Relevant literature was reviewed to ensure a comprehensive assessment and establish a criterion system.

Furthermore, the present study conducted a fuzzy-Delphi study to validate the identified factors impacting solar farm selection through the literature review. The purpose of validating the factors is to adjust the identified factors to the case study of the present research, the Baltic region. Factors were extracted from different studies on case studies worldwide; therefore, refining and validating factors are crucial. To this end, ten academic experts validated the identified factors using fuzzy-Delphi. The steps of fuzzy-delphi are presented in Appendix 4. Table 1 shows experts' support using linguistic variables and the final results of Fuzzy Delphi. Aggregated values for each factor were calculated after assigning the equivalent fuzzy numbers for each linguistic variable. Afterward, the crisp value was calculated through defuzzification, and if the crisp value was less than 0.5, the factor was rejected (Ismail et al., 2019; Petrudi et al., 2022).

4.1. Stage 1. DEA

Based on the Fuzzy Delphi results, the input and output factors for

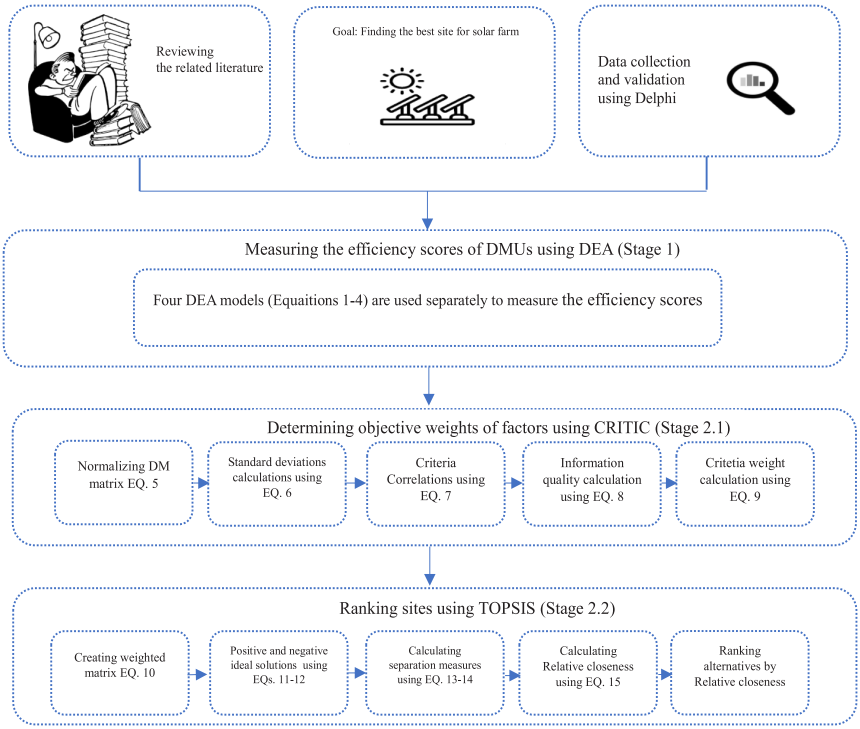

Fig. 1. Research steps.

Table 1
Experts' support and results.

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	Aggregated Value	Defuzzification	Status
Solar irradiation	SA	SA	TA	A	A	TA	TA	A	SA	SA	A(0.50,0.90,1.00)	0.800	Accept
Air temperature	TA	TA	TA	SA	SA	SA	SA	A	SA	TA	A(0.50,0.96,1.00)	0.822	Accept
Slope	A	D	A	NS	D	TD	D	D	TD	A	A(0.00,0.33,0.90)	0.409	Reject
Land aspects	TD	D	D	TD	D	NS	TD	TD	A	A	A(0.00,0.24,0.90)	0.380	Reject
Proximity to urban areas	NS	A	TD	A	A	D	A	D	A	TD	A(0.00,0.39,0.90)	0.429	Reject
Proximity to roads	A	TD	NS	D	NS	A	NS	TD	D	A	A(0.00,0.36,0.90)	0.421	Reject
Proximity to power lines	TD	A	D	TD	A	A	NS	NS	A	TD	A(0.00,0.34,0.90)	0.412	Reject
Proximity to protected areas	NS	NS	D	NS	D	TD	TD	NS	A	D	A(0.00,0.32,0.90)	0.407	Reject
Transport infrastructure	D	NS	A	A	NS	TD	NS	TD	A	NS	A(0.00,0.38,0.90)	0.427	Reject
Humidity	SA	SA	SA	A	SA	TA	A	SA	SA	A	A(0.50,0.90,1.00)	0.800	Accept
Air pressure	A	SA	TA	A	A	TA	SA	SA	SA	TA	A(0.50,0.90,1.00)	0.800	Accept
Sunshine duration	SA	TA	SA	TA	A	SA	TA	SA	TA	SA	A(0.50,0.96,1.00)	0.822	Accept
Elevation	A	TA	A	A	A	SA	TA	TA	SA	TA	A(0.50,0.87,1.00)	0.789	Accept
Proximity to rural areas	A	A	A	NS	A	D	TD	D	NS	D	A(0.00,0.42,0.90)	0.439	Reject
Proximity to tourist areas	D	A	NS	NS	A	NS	TD	TD	A	NS	A(0.00,0.38,0.90)	0.427	Reject
Geological rock type	D	TD	TD	A	NS	D	TD	NS	TD	A	A(0.00,0.25,0.90)	0.385	Reject
Distance from bird migration routes	A	A	A	D	NS	A	TD	NS	A	D	A(0.00,0.45,0.90)	0.452	Reject
Distance from faults	D	TD	A	NS	TD	NS	A	A	TD	A	A(0.00,0.34,0.90)	0.412	Reject
Distance from rivers	TD	NS	A	A	D	NS	D	TD	D	D	A(0.00,0.32,0.90)	0.405	Reject
Distance from water surfaces	A	D	D	NS	TD	TD	A	TD	D	D	A(0.00,0.27,0.90)	0.390	Reject
Distance from the railway transportation network	D	TD	D	NS	NS	TD	NS	NS	TD	D	A(0.00,0.26,0.70)	0.322	Reject
Wind speed	SA	SA	SA	A	TA	SA	SA	A	A	TA	A(0.50,0.90,1.00)	0.800	Accept
Precipitation	TA	A	TA	A	TA	A	TA	SA	TA	TA	A(0.50,0.90,1.00)	0.800	Accept

the DEA model are selected and defined as follows.

Input factors:

- **Temperature (I1)**: In the case of solar modules, even a minor temperature increase can significantly impact their overall performance (Sindhu et al., 2017). This change can decrease efficiency and output power, harming their functionality. Therefore, monitoring and regulating the temperature of solar modules is crucial to ensure that they operate optimally (Gherboudj and Ghedira, 2016).

- **Wind Speed (I2)**: The movement of gas particles is known as wind. To ensure the durability of solar installations, they must withstand the wind load and uplift caused by wind (Wang et al., 2021a). Operational failures and wear and tear of systems can also be caused by wind. Additionally, high wind speeds can increase dust particles adhering to the surface of solar modules, reducing their power output (Watson and Hudson, 2015; Qolipour et al., 2016).
- **Humidity (I3)**: The term humidity refers to the level of water vapor present in the air. Water droplets in the air can refract, reflect, or bend the sunlight (Sindhu et al., 2017). This situation means that air humidity can affect the amount of radiant energy from the sun that reaches solar panels, reducing their efficiency (Doorga et al., 2019; Zoghi et al., 2017). If the humidity is too high, it can cause dew to form on the solar panels' surface, making it easier for dust from the air to accumulate on them, leading to a decrease in the output power of the solar modules (Gherboudj and Ghedira, 2016; Watson and Hudson, 2015).
- **Precipitation (I_4):** Various forms of precipitation, such as rain, snow, sleet, or hail, occur when the moisture-filled clouds in the sky release their contents (Lisauskas et al., 2022). As a result, when these clouds darken the sky and block the sun's rays, solar power plants' energy is decreased.
- **Air Pressure (I_5):** The weight of the air on the earth's surface creates air pressure. As altitude increases, air pressure decreases, and the temperature also drops. This drop in temperature enables the solar system to function more efficiently. If there were fewer layers of air, direct sunlight would have a more significant impact, as there would be less scattering, absorption, and reflection of sunlight.

Outputs factors:

- **Sunshine hour (O_1):** It refers to when a specific location receives direct sunlight during a given year. This type of sunlight is known as solar radiation and is defined as having a strength of 120 W per square meter or more (Sindhu et al., 2017). The amount of solar energy a solar panel produces is directly affected by the duration of sunshine hours (Doorga et al., 2019; Zoghi et al., 2017).
- **Irradiation (O_2):** It pertains to the amount of solar energy quantified in kilowatt-hours (kWh) a particular surface area receives that, often expressed in square meters (m2), during a definite duration, typically a year (Sindhu et al., 2017; Gherboudj and Ghedira, 2016).
- **Elevation (O_3):** The altitude of a region can affect its solar potential. Solar panels placed at higher elevations can capture more sunlight as there is less atmospheric absorption at higher altitudes (Doorga et al., 2019). In other words, the thinner atmosphere at high altitudes increases solar energy availability (Zoghi et al., 2017).

Data for input and output factors from 39 locations is included in Table 2. The present study used RETScreen Expert to collect data for 2021. RETScreen Expert, a component of the RETScreen Clean Energy Management Software developed by the Canadian government, is a

Table 2
Inputs and outputs for the DEA models.

DMU	Temperature (°C)	Wind speed (m/s)	Humidity (%)	Precipitation (mm)	Air pressure (kPa)	Irradiation (Kwh/m^2/d)	Elevation (m)	Sunshine duration (h/y)
Vilnius	6.6112	3.8395	78.9649	765.58	99.6577	1034.4	156	1597
Alytus	6.2142	3.5669	84.2614	729.9	99.9202	1040.1	131	1730
Kaunas	6.3849	3.9737	79.4038	747.31	100.5692	1034.1	77	1764
Klaipėda	7.7477	4.5981	79.6923	813.64	101.0801	1084.1	7	1825
Telšiai	6.103	4.0429	86.363	784.02	100.291	1023	93	1780
Panevėžys	5.8145	2.8873	86.277	761.81	100.5925	1025.8	70	1743
Šiauliai	6.7778	2.7564	79.1115	745.42	100.2085	1030.8	107	1791
Utena	6.6271	2.1479	77.5732	805.43	99.8909	1024.9	106	1686
Mažeikiai	6.0197	4.4012	86.3312	756.71	100.2876	1025.1	91	1790
Šilalė	6.3362	3.1959	82.1515	784.02	100.291	1032.3	166	1777
Birzaj	6.8345	3.1479	78.9986	795.21	100.6499	1030.3	62	1734
Daugavpils	6.131	2.8066	78.7836	791.43	99.7476	1019	122	1686
Rezekne	5.729	2.9721	76.7419	790.61	99.9333	1013	157	1839
Līvāni	5.1425	2.4268	87.0036	788.15	100.0375	1012.7	114	1703
Jēkabspils	4.9921	3.0705	87.457	827.74	99.9401	1026.9	120	1723
Jelgava	6.1315	4.9188	85.6997	727.24	101.0541	1020	27	1760
Riga	7.5636	3.4721	79.0479	727.24	101.0541	1026.2	26	1778
Liepaja	7.4641	3.8822	81.0836	792.43	100.9734	1078.9	7	1835
Ventspils	6.8668	5.7078	85.0989	710.56	100.9908	1058.9	28	1837
Kolka	6.8222	3.7559	81.2225	699.68	101.1841	1048.4	5	1780
Mersrags	6.5381	2.9638	79.6389	722.33	101.0732	1025.3	6	1678
Ainazi	6.3874	4.18	80.64	773.81	101.0956	1052.7	5	1830
Valga	5.9142	2.0896	80.6836	786.36	100.1599	983.6	66	1670
Valmiera	5.2022	4.8452	86.7644	784.74	100.4815	997.5	71	1760
Gulbene	5.6214	3.0893	79.1803	790.33	99.8483	999.1	143	1836
Võru	4.5216	4.6184	87.186	813.2	100.1582	982.1	99	1683
Viljandi	4.9132	4.745	86.1841	771.94	100.539	988.7	64	1970
Parnu	6.4074	3.8247	80.4773	765.04	100.8539	1019.5	8	1975
Ristna	6.8658	3.966	81.551	719.38	101.1907	1051.6	9	1995
Haapsalu	6.1079	5.5965	85.2233	713.09	101.1006	1034.8	15	1980
Tallin	5.8701	3.6225	80.1118	727.94	100.8272	999	34	1930
Kunda	5.8216	3.7814	79.2501	712.57	101.0112	985	3	1934
Kohtla-Järve	4.8304	4.4233	85.8184	787.8	100.7563	989.5	44	1723
Narva	5.6564	3.4729	77.8058	840.22	100.7603	987.1	30	1668
Rakvere	4.8129	5.4752	85.4151	750.04	100.4889	985.7	65	1910
Tapa	4.9866	5.5451	85.3803	744.2	100.5339	972	61	1610
Valke-Maarja	5.1781	3.6633	79.8605	750.04	100.4889	984.9	123	1595
Turi	5.8301	2.431	79.7956	758.76	100.6065	975.1	65	1974
Tartu	5.7992	3.6488	78.6274	798.57	100.4497	991.1	68	1660

pivotal tool for low-carbon planning and project implementation. This free software empowers energy professionals to evaluate and optimize clean energy initiatives' technical and financial aspects. By offering decision support, RETScreen Expert plays a crucial role in enhancing the viability and performance of renewable energy projects, contributing to effective decision-making in pursuing sustainable and efficient energy solutions. Fig. 2 illustrates the potential locations in the Baltic region.

Table 3 provides a statistical analysis of these factors, including maximum, minimum, average, and standard deviation values. This data will be utilized to carry out the CCR-I, CCR-O, BCC-I, and BCC-O models to determine potential locations (DMUs) with an efficiency score of 1.

4.2. Stage 2. CRITIC-TOPSIS

In the second phase, the selected DMUs will undergo analysis using the CRITIC-TOPSIS approach. The selected DMUs were analyzed according to the following criteria:

- **Labor force:** It is necessary to have well-trained human resources with expertise in solar exposure, installation, and maintenance to operate PV power plants effectively. It would be advantageous to have skilled individuals in the local area (Saraji and Streimikiene, 2023). As the PV industry expands, the demand for competent workers to carry out installation, maintenance, and repair tasks is expected to increase (Sindhu et al., 2017).
- **GDP:** Generally, countries with higher GDP levels have more financial resources to invest in various sectors, such as renewable energy. These countries may be more likely to allocate resources and implement supportive policies for projects like solar farms (Do et al., 2020). Countries with higher GDPs can also invest more in research and development (R&D) activities. Higher GDP levels often coincide with better infrastructure, including electrical grids and transmission networks (Vafaeipour et al., 2014b). Furthermore, countries with higher GDP typically consume more energy due to increased industrial activity and higher living standards (Saraji et al., 2023).
- **Land acquisition:** It is important to consider land acquisition when implementing renewable energy technologies. These technologies may require fertile land and forests or impact biodiversity (Deveci et al., 2021). When selecting sites for solar farms, it is crucial to have a clear and timely process for acquiring land, including obtaining agreement from occupants to prevent legal issues. Additionally, it should be ensured that only degraded land is utilized for photovoltaic development (Anwarzai and Nagasaka, 2017). In the present study, the total area under forest is considered as an indicator to measure land availability for building solar farms (Carrión et al., 2008).
- **Performance and efficiency:** Understanding the efficiency and performance of a solar power installation requires knowledge of its specific photovoltaic power output (Al Garni and Awasthi, 2017). This metric varies depending on panel types, installation configurations, and regions. Evaluating the potential performance of a photovoltaic system requires considering these factors (Saraswat et al., 2021).
- **Technical issues by environment:** The efficiency of a PV system is influenced by site-specific factors, including latitude, air pollution levels, and the cloudiness of the season (Ozdemir and Sahin, 2018). In the Baltic region, the depth of snow is a crucial climate factor affecting the performance of solar farms. When snow blankets the solar panels, it obstructs sunlight from reaching the photovoltaic cells that generate electricity (Yun-na et al., 2013). The snow accumulation on the panels can also delay the melting process, mainly if temperatures are low. Therefore, snow depth can significantly impact the effectiveness of PV systems in this region (Watson and Hudson, 2015).

5. Results

During the initial phase of implementing DEA models for solar energy deployment, it is possible to filter out potential areas suitable for solar installation based on various measurable criteria. These criteria can be categorized into two types: inputs and outputs. Inputs include air temperature, wind speed, relative humidity, and precipitation, while outputs include sunshine hours, irradiation, and elevation. By analyzing these criteria, DEA models can determine the areas most suitable for solar energy deployment, helping to maximize the efficiency and effectiveness of solar installation projects (Chandra et al., 2018).

Fig. 2. Baltic region and potential locations for building solar farms.

Table 3
Statistical analysis of inputs and outputs.

Factor	Average	Sum	Variance	SD	Max	Min
Air temperature	6.0405	235.5782	0.6031	0.7766	7.7477	4.5216
Wind speed	3.7834	147.5525	0.8757	0.9358	5.7078	2.0896
Relative humidity	82.0734	3200.861	11.0209	3.3198	87.457	76.7419
Precipitation	765.4997	29854.49	1209.6152	34.7795	840.22	699.68
Irradiation	1017.7744	39693.2	754.1675	27.4621	1084.1	972
Elevation	67.9744	2651	2371.307	48.6961	166	3
Air Pressure	100.5328	3920.7774	0.1987	0.4457	101.1907	99.6577
Sunshine duration	1783.0513	69,539	12076.9204	109.895	1995	1595

In the DEA, a DMU (Decision-Making Unit) is considered to have better efficiency when its output is more significant and its input is lower. For PV systems, wind speed and precipitation are two essential inputs that affect their efficiency. However, weaker winds and lower rainfall are considered preferable for PV systems. While wind speed naturally cools the PV modules and rain helps remove dirt, dust, or pollen from the panels, enhancing the system's efficiency, their negative impact on the system's long-term operation cannot be ignored. In fact, wind speed and precipitation are considered dominant and long-term factors that can cause operational outages in PV systems. In addition to these inputs, air temperature is essential to the efficiency of solar power plants. Therefore, it is crucial to consider all these factors while designing and operating PV systems and solar power plants to ensure their maximum efficiency and optimal performance. From DEA analysis, efficiency scores achieved by the DMUs are depicted in Table 4. According to the results, 25 DMUs achieved perfect efficiency scores in DEA analysis. However, only six sites located in Lithuania have been listed as efficient sites, including Vilnius, Alytus, Klaipėda, Šiauliai, Utena, and Šilalė.

Table 4
The efficiency score of locations in the DEA models.

DMU	CCR-I	CCR-O	BCC-I	BCC-O
Vilnius	1	1	1	1
Alytus	1	1	1	1
Kaunas	0.9986	1.0014	0.9988	1.0012
Klaipėda	1	1	1	1
Telšiai	0.9842	1.016	0.9842	1.016
Panevėžys	0.9973	1.0027	0.9991	1.0009
Šiauliai	1	1	1	1
Utena	1	1	1	1
Mažeikiai	0.9876	1.0125	0.9881	1.012
Šilalė	1	1	1	1
Birzaj	0.9835	1.0167	0.9838	1.0165
Daugavpils	0.996	1.004	1	1
Rezekne	1	1	1	1
Līvāni	1	1	1	1
Jēkabspils	1	1	1	1
Jelgava	0.9797	1.0207	0.9821	1.0182
Riga	0.9938	1.0062	1	1
Liepaja	1	1	1	1
Ventspils	1	1	1	1
Kolka	1	1	1	1
Mersrags	1	1	1	1
Ainazi	1	1	1	1
Valga	1	1	1	1
Valmiera	0.9778	1.0227	0.9784	1.022
Gulbene	0.9947	1.0053	1	1
Võru	1	1	1	1
Viljandi	1	1	1	1
Parnu	1	1	1	1
Ristna	1	1	1	1
Haapsalu	1	1	1	1
Tallin	1	1	1	1
Kunda	1	1	1	1
Kohtla-Järve	0.9926	1.0074	0.9932	1.0069
Narva	0.9731	1.0277	0.9731	1.0277
Rakvere	1	1	1	1
Tapa	0.9809	1.0194	1	1
Valke-Maarja	1	1	1	1
Turi	1	1	1	1
Tartu	0.9674	1.0337	0.9689	1.0321

In the next step, a methodology called CRITIC-TOPSIS was employed to identify the most suitable location in Lithuania based on the specific criteria outlined in Section 3.2. These criteria included factors such as the labor force's availability, GDP level, extent of forest cover, potential for photovoltaic power generation, and average snowfall. The resulting decision-making matrix is presented in Table 5, which provides a comprehensive overview of the various locations and their relative strengths and weaknesses concerning each criterion.

The results of the CRITIC method are shown in Table 6. The CRITIC helps identify the importance of each criterion by analyzing their correlations. This method leads to more transparent and informed decision-making by quantifying the relationships between criteria and helping decision-makers allocate weights based on the inter-criteria correlations.

According to the analysis of the CRITIC method, it was found that the specific photovoltaic power output is the most essential criterion for selecting a location for building solar farms, followed by the labor force criterion, which was also found to have a significant influence. After applying the TOPSIS method to rank the locations based on the weighted criteria, the results were tabulated in Table 7. Based on these criteria, the study concluded that the best location for building solar farms is Vilnius, followed by Klaipėda.

5.1. Sensitivity analysis

Table 6 shows that the specific photovoltaic power output is fundamental in determining the ideal solar farm. This factor serves as a metric for the amount of electrical power generated per unit of area or installed capacity by a PV system. It is influenced by several variables, including the solar farm's location, panel tilt and orientation, panel efficiency, temperature, degree of shading, accumulation of dust and dirt, system design and components, and system aging. Therefore, it is essential to meticulously consider each factor when selecting the most suitable solar farm for a project. The recently released map by the Global Solar Atlas, as shown in Fig. 3, offers compelling insights into the potential of photovoltaic power in Lithuania. Interestingly, the map suggests that Klaipėda may be a more favorable location for solar farm construction than Vilnius. This finding may come as a surprise, as it differs from the

Table 5
Decision-making matrix.

Sites	labor force-Thousands	GDP-EUR thousand	Forest-%	Specific photovoltaic power output-kWh/kWp-Yearly	Average snow depth-CM
Vilnius	471.5	25.6	33.6	1020.2	22
Alytus	68.5	10.6	32.5	1044.6	17
Klaipėda	164.4	16.4	19.9	1114.7	14
Šiauliai	130.7	13.4	6	1051.7	20
Utena	58.2	10.5	33.9	1039.3	23
Šilalė	48.3	9.7	47.3	1056.5	32

Table 6
The CRITIC results.

Criteria	σ_j	ν_j	ϖ_j	Rank
labour force-Thousands	63.963	262.538	0.109	2
GDP-EUR thousand	5.747	21.829	0.009	5
Forest-%	11.603	44.229	0.018	3
Specific photovoltaic power output-kWh/kWp-Yearly	430.350	2046.165	0.851	1
Average snow depth-CM	8.468	29.797	0.012	4

Table 7
The TOPSIS results.

Sites	S^+	S^-	C*	Rank
Vilnius	0.0319	0.08799	0.7342	1
Alytus	0.0871	0.01031	0.1059	5
Klaipėda	0.0639	0.04014	0.3860	2
Šiauliai	0.0738	0.02246	0.2334	3
Utena	0.0896	0.00763	0.0784	6
Šilalė	0.0906	0.01195	0.1166	4

results presented in Table 6 of the current study. A sensitivity analysis was performed to understand this disparity, which should further clarify the underlying factors involved.

GDP and labor force were non-technical criteria; therefore, these two criteria were excluded from the analysis process to check whether the results would change and would be in line with the graph provided by Global Solar Atlas. Table 8 shows the final results of the sensitivity analysis.

According to the sensitivity analysis results, Klaipeda is the best site, followed by Šiauliai, Šilalė, Alytus, Utena, and Vilnius; therefore, the results of the sensitivity analysis are in line with the Global Solar Atlas' report. Fig. 2 compares the results of CRITIC-TOPSIS and sensitivity analysis. The impact of non-technical criteria is evident as relative closeness has changed for Vilnius dramatically, while it was the best site according to all technical and non-technical criteria.

5.2. Comparative studies

This section compares the present study results with the SWARA-COPRAS under picture fuzzy sets. The SWARA method determines the subjective weights of factors shown in Fig. 4. The reason for applying the SWARA is to see the impact of subjective weight on the final results since the present study used CRITIC to determine the objective weights of factors. Also, the COPRAS is used to rank cities in Lithuania according to weighted criteria and compare the results with the TOPSIS method to see whether changes in the ranking method would impact the final

Table 8
Sensitivity analysis results.

Sites	S^+	S^-	C*	Rank
Vilnius	0.0319	0.00398	0.1110	6
Alytus	0.0239	0.00942	0.2824	4
Klaipėda	0.0033	0.03206	0.9067	1
Šiauliai	0.0208	0.01454	0.4115	2
Utena	0.0258	0.00734	0.2217	5
Šilalė	0.0219	0.01195	0.3529	3

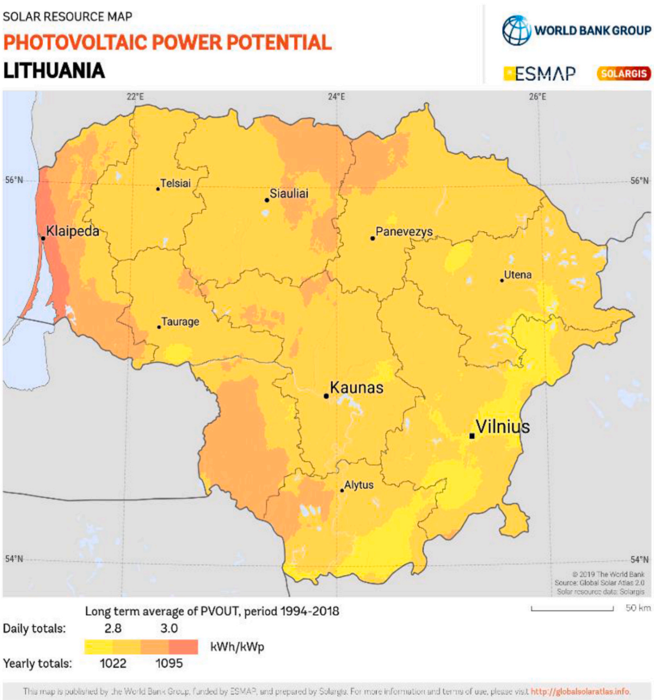

Fig. 3. Potential of photovoltaic power in Lithuania.

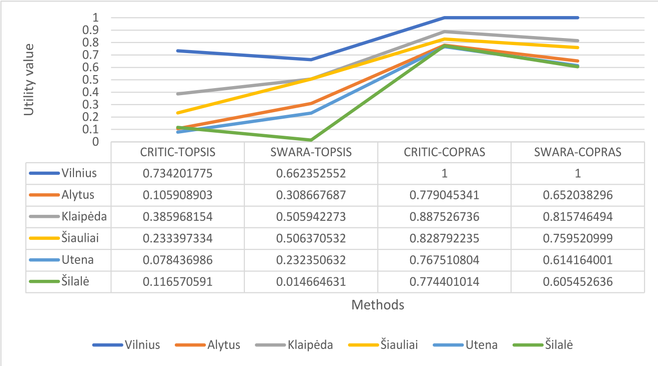

Fig. 4. Comparative analyses.

results. Moreover, using SWARA and linguistic variables to determine the subjective weight of factors results in imprecise communication of expert judgments, leading to ambiguity in the thinking mode. Consequently, fuzzy numbers are more appropriate and recommended for evaluating alternatives over the crisp numbers approach. Therefore, Picture Fuzzy Sets (PFs), a new fuzzy extension, are employed to handle uncertainty in decision-making. The steps of the PF-SWARA-COPRAS are presented in Appendix 5. The results of comparative analyses are shown in Fig. 4.

Based on the results of all the methods analyzed, it has been determined that Vilnius is the most suitable location for building solar farms. However, when depicting the differences between the utility values, the CRITIC-TOPSIS method outperformed the CRITIC-COPRAS approach. Therefore, the proposed method is considered the most accurate in identifying the optimal location for installing solar farms.

Furthermore, the proposed method also revealed that Šilalė is not the worst option, which aligns with the sensitivity analyses and the Global Solar Atlas data. This result further confirms the superiority of the proposed method over other approaches. Overall, the results obtained from the proposed method provide a comprehensive and accurate analysis of the best location for building solar farms in the region.

6. Discussion

According to appendices 1 to 3, it was found that most studies utilized the GIS-AHP approach in selecting sites for constructing solar farms, such as Raza et al. (2023), Kocabaldır and Yücel (2023), Tafula et al. (2023), and Di Grazia and Tina (2023). One of the main advantages of GIS over other methods is its ability to analyze an entire area and a range of potential locations. This difference means that GIS can be applied to determine suitable sites for solar farms across an entire country, while other methods may only be applicable to specific locations. However, it is essential to note that GIS relies on map layers and buffers, whereas methods like DEA rely on complex mathematical models, making DEA a more reliable option. As a result, mathematical models are typically more accurate and reliable when it comes to selecting the best site among a set of predetermined locations, which is in line with studies conducted by Hassan et al. (2023b), Qasimi et al. (2023), and Vagiona et al. (2022). On the other hand, GIS should be used primarily for determining the best area for constructing solar farms rather than pinpointing specific locations. By utilizing both methods in conjunction, researchers can ensure that they select the most optimal location to construct a solar farm while considering a wide range of factors, including environmental impact, local regulations, and accessibility, which align with Bandira et al. (2022) and Yousefi et al. (2018).

Furthermore, Most studies applied AHP to determine criteria weights and rank locations. AHP involves the creation of complex hierarchical structures and pairwise comparisons, which can be time-consuming and require expert judgment, while TOPSIS does not require the extensive pairwise comparison of criteria and alternatives that AHP does, which it inline with Wang et al. (2022b), Anser et al. (2020), and Lee et al. (2015). This feature simplifies decision-making, especially when dealing with many criteria or alternatives. Also, AHP assumes linear relationships between criteria, which may not always accurately represent real-world decision scenarios, while TOPSIS can handle non-linear relationships between criteria and alternatives effectively. TOPSIS uses Euclidean distance or other distance metrics to accommodate non-linear preferences.

Moreover, when it comes to evaluating and prioritizing different criteria, various methods are available. One such method is the CRITIC method, which relies on statistical analysis and data to determine the weights of different criteria. This approach is beneficial when there is reliable and ample data available. Compared to other methods like AHP, which rely on subjective criteria weighting, the CRITIC method generates objective results. This feature makes it a better fit for scenarios needing unbiased and data-driven decision-making, which aligns with Hassan et al. (2023b). The CRITIC method is also transparent and reproducible, based on mathematical procedures and statistical analysis. This feature enhances the credibility of the criteria weighting process and makes it easier for decision-makers to understand and trust the results. The CRITIC method is reliable and robust for determining criteria weights in various scenarios.

While considering GDP and labor force in selecting solar farm sites can be advantageous, it also has its downsides. Focusing solely on GDP can result in an overconcentration of solar farms in prosperous areas, disregarding regions with lower GDP that could benefit from renewable energy initiatives. Moreover, areas with a strong labor force may encounter increased job competition, leading to wage inflation and workforce shortages in other industries. An overemphasis on these factors may also neglect a site's ecological and environmental suitability, which could harm local ecosystems or compromise the long-term sustainability of solar projects. Hence, a well-rounded approach considering various factors, including environmental and community impacts, is crucial for responsible solar farm site selection.

7. Conclusions

This innovative two-stage approach gives decision-makers a valuable tool to pinpoint the most optimal locations for building solar farms. This method comprehensively analyzes potential sites by considering many factors - such as climate, social, economic, and technical criteria. The initial stage of the approach employs DEA to evaluate sites based on their climate suitability, ensuring that only the most efficient options are considered. In the second stage, the method applies CRITIC-TOPSIS to identify the best site from the remaining potential and efficient sites, considering a broader range of factors. With its meticulous and analytical approach, decision-makers can confidently decide where to construct solar farms, maximizing their effectiveness and efficiency. Furthermore, it can be inferred that the findings align with the information presented by the Global Solar Atlas, assuming that social and economic aspects are not considered. This finding implies that businesses can select solar farms based on technical and climate-related criteria while ensuring they meet the necessary social and economic standards. This finding could prove helpful for companies looking to establish their solar farms, as it highlights the importance of considering technical and non-technical factors in decision-making.

Integrating DEA in the first stage and CRITIC-TOPSIS in the second stage for all solar farm site evaluations ensures a comprehensive assessment of potential sites, considering climate suitability, technical efficiency, and broader social, economic, and technical criteria. Also, climate suitability is the primary factor in the initial evaluation stage of the solar farm site, ensuring that only the most efficient options for solar energy generation potential are considered, aligning with the findings of the two-stage approach. In the second site evaluation stage, a more comprehensive set of criteria, such as social, economic, and technical factors, alongside climate suitability should be included. This policy ensures a holistic assessment of potential sites, considering technical feasibility and social and economic implications, aligning with the comprehensive analysis approach. Guidelines and best practices should be developed for businesses looking to install solar farms, emphasizing the importance of considering technical and non-technical factors in decision-making. This policy helps companies make informed decisions when selecting solar farm locations and evaluating technical feasibility while meeting social and economic standards. A process for periodic review and update of the criteria and models used in the two-stage approach should be established to ensure its continued relevance and accuracy. Continuous improvement and adaptation of the approach will enable decision-makers to make well-informed choices for solar farm locations as technology and circumstances evolve.

One of the main limitations of the present research was the need for more data to be available for some sites in the Baltic region. As a result, the present research had to remove these sites from the analyses, which could have affected the overall accuracy and completeness of the findings. Additionally, conducting a fuzzy Delphi method to validate the identified factors was a time-consuming process that required significant effort from the researchers. Despite these limitations, the present research represents an essential contribution to the field, providing valuable insights into the factors most relevant to studying the Baltic marine environment. Furthermore, it is recommended to redo analyses using other methods for determining objective weights, such as the method based on the removal effects of criteria (MEREC), and compare the results with the present study. Also, it is recommended to apply the present two-stage model in other countries to evaluate its applicability. Also, it is recommended that other DEA models be applied and the results obtained be compared with the present study.

CRediT authorship contribution statement

Mahyar Kamali Saraji: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Dalia Streimikiene:** Writing – review & editing, Supervision, Conceptualization. **Vishnu Suresh:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation.

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.

Appendix 1. GIS-AHP application for site selection

Author(s) and year	Country	Method(s)	Case study location	Included factors
Al Garni and Awasthi (2017)	Saudi Arabia	GIS and AHP	The whole country	Solar irradiation, air temperature, slope, land aspects, proximity to urban areas, proximity to roads, proximity to power lines
Mensour et al. (2019)	Morocco	GIS and AHP	Souss-Massa area	Solar irradiation, land use, distance to urban areas, slope, and distance to transmission lines
Sun et al. (2021)	China	GIS and AHP	Five lands	Protected area, land cover, transport infrastructure, and orography
Colak et al. (2020)	Turkey	GIS and AHP	Malatya province	Land cover, slope, aspect, and solar energy potential
Finn and McKenzie (2020)	EU	GIS and AHP	462 sites	Aspect, slope, land cover, distance from transport
Noorollahi et al. (2022)	Iran	GIS and AHP	Khuzestan province	Humidity, temperature, pressure, sunshine hour, slope, irradiation, land use, elevation, distance from urban and rural areas
Raza et al. (2023)	Pakistan	GIS and AHP	The whole country	Solar irradiation, average temperature, land cover, slope, land aspects, proximity to urban area, proximity to roads, and proximity to power lines
Kocabaldır and Yücel (2023)	Turkey	GIS and AHP	Çanakkale province	Solar irradiation, average temperature, land cover, slope, land aspects, proximity to urban area, proximity to roads, and proximity to power lines
Tafula et al. (2023)	Mozambique	GIS and AHP	Ten sites	Humidity, temperature, pressure, sunshine hour, slope, irradiation, land use, elevation, distance from roads, job opportunities, energy justice, human development index
Di Grazia and Tina (2023)	Italy	GIS and AHP	47 basins in Sicily	Costs of the plant, the distance of the plants from nearby medium voltage connection, the annual energy yield by the plant, levelized cost of energy, CO2 emissions
Uyan (2017)	Turkey	GIS and AHP	The Ayranci region in Karaman	Distance from residential areas, land use, slope, distance from transmission lines, and distance from roads
Kırcalı and Selim (2021)	Turkey	GIS and AHP	Antalya state	Solar radiation, annual average temperature, sunshine duration, distance to transformers, distance to residential areas, distance to roads, slope, aspect, land use, and elevation
Nguyen et al. (2022)	Vietnam	GIS and AHP	Binh Thuan province	solar radiation, land surface temperature, distance to substation, main road, residential area, historical and tourism sites, land use, and slope

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Author(s) and year	Country	Method(s)	Case study location	Included factors
Koc et al. (2019)	Turkey	GIS and AHP	Igdir Province	Elevation, land cover, aspect, inclination, geological rock type, solar irradiance, temperature, and transmission line
Günen (2021)	Turkey	GIS and AHP	Kayseri state	GHI, aspect, slope, land use, distance from bird migration routes, distance from faults, distance from rivers, distance from water surfaces, distance from power lines, distance from road transportation network, distance from railway transportation network, and distance from transformer center
Arca et al. (2023)	Turkey	GIS and AHP	Safranbolu state	Solar radiation, aspect, slope, land use, distance to road, residential areas, and fault
Suuronen et al. (2017)	Chile	GIS and AHP	Atacama Desert	Slope, orientation, GHI, temperature, highway access, distance to grid, biomass, and land use
Ali et al. (2022)	Thailand	GIS and AHP	15 sites	Hydrogen generation potential, proximity to major urban centers, slope, elevation, distance to road and transmission lines, Land type used, and distance to residential and protected areas
Halder et al. (2022)	India	GIS and AHP	Megacity Kolkata	Solar radiation, LULC, water body, residential area, power supply Line, soil type, highway, protected area, slope, aspect, and altitude
Merrouni et al. (2018)	West Africa	GIS and AHP	Rural areas	Urban settlements, land cover, risk areas, protected areas, land slope, population density

Appendix 2. GIS application for site selection

Author(s) and year	Country	Method(s)	Case study location	Included factors
Hasti et al. (2023)	Iran	GIS, AHP, TOPSIS, and ANP	29,000 Sites	Meteorology, Topology and shape of the earth, Human infrastructure, Supplementary criteria
Shorabeh et al. (2019)	Iran	GIS and Ordered Weighted Averaging (OWA)	Four states	Slope, distance from roads, NDVI, LST, solar radiation, rainfall, distance from the fault
Wang et al. (2016)	China	GIS	4005 Sites	Time series of solar radiation data, land cover data, and digital elevation model data
Besharati Fard et al. (2022)	Iran	Fuzzy best-worst method-GIS	Guilan province	Distance from urban, rural, historical areas, and main roads; distance from power lines, slope, land use, wind, temperature, and irradiation
Heo et al. (2021)	South Korea	building information model (BIM)-GIS	Ucheon-myeon district	Slope, PV output per capacity per hour, highway networks, and lake
Bandira et al. (2022)	Malaysia	GIS-based multicriteria evaluation methodology	George Town region	Distance from urban and main roads; distance from power lines, slope, land use, humidity, elevation, GHI, precipitation, wind speed, temperature, and irradiation
Yousefi et al. (2018)	Iran	GIS-Based Boolean-Fuzzy Logic model	Markazi province	Distance from urban, rural, protected areas, and main roads, slope, land use, and elevation
Guaita-Pradas et al. (2019)	Spain	GIS	Valencian Community	Time series of solar radiation, digital elevation models (DEM), land cover, and temperature
Uyan and Dogmus (2023)	Turkey	GIS and ANP	Cumra Region	Aspect, distance from transmission lines, distance from surface waters, distance from transformer center, distance from residential areas, and distance from roads and railways
Khan et al. (2023)	Pakistan	GIS-FUCOM	The whole country	Solar radiation, aspect, temperature, land use, distance to road, residential areas, and transmission lines
Hashemizadeh et al. (2020)	China	GIS-BWM	Beijing state	Protected land, urban area, solar potential, waterways, roads and railways, DEM, and transmission power line
Merrouni et al. (2018)	Spain	GIS-AHP-TOPSIS	South-eastern Spain	Agrological capacity, land slope, land orientation, plot areas, distance to villages, distance to main roads, distance to substations, distance to power lines, solar irradiation potential, average temperature
Sánchez-Lozano et al. (2014)	Spain	GIS-ELECTRE TRI	Torre Pacheco and Murcia	Agrological capacity, slope, area, field orientation, distance to main roads, distance to power lines, distance to cities, distance to electricity transformer substations, and Potential solar radiation
Merrouni et al. (2018)	Morocco	GIS-AHP	Eastern Morocco	Direct normal irradiation, slop, distance from residential, distance from road and railway network, distance from electricity grid, distance from waterways, distance from dams, and distance from underground water

Appendix 3. Applied method for selecting solar farm sites

Author(s) and year	Country	Method(s)	Case study location	Included factors
Vafaeipour et al. (2014a)	Iran	SWARA, WASPAS, Delphi	25 Sites	Investment cost, maintenance cost, NPV, payback period, solar irradiation, land availability, transmission grid accessibility, social acceptability, demand for electricity, political risk, economic risk, environmental risk, and time delay
Ahadi et al. (2023)	Iran	AHP	31 provinces	The amount of radiation, sunny days, temperature, humidity, rainfall, air pollution, cloudiness
Hafeznia et al. (2017)	Iran	Fuzzy operators and boolean logic	2005 ha	Safety, Socioeconomic, geographical, environmental, technical
Sun et al. (2023)	China	Multi-layer perceptron, random forest, extreme gradient boosting models	The whole country	Land cover, slope, aspect, average elevation, distance to water resources, land cost, transportation convenience, distance to residential area, population density, GDP, solar irradiation, and sunshine duration

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(*continued*)

Author(s) and year	Country	Method(s)	Case study location	Included factors
Rogna (2020)	Italy	Pareto dominance method	47,662 sites	Land size, PV peak power, system losses, plant cost, interest rate, plant lifetime, operating costs, and land opportunity cost
Jung et al. (2019)	South Korea	Mathematical estimation methods	10	SEM, aspect, and slope
Xiao and Wang (2019)	China	Probabilistic linguistic term set, VIKOR, and Heronian mean operator	Seven sites	Construction and maintenance costs, land availability, social acceptance, effect on the development of surrounding areas, political risk, economic risk, environmental risk, solar irradiation, sunshine duration, and annual effective sunshine
Wu et al. (2021)	China	BWM-CRITIC- the multi-attributive border approximation area comparison (MABAC) and probabilistic hesitation fuzzy linguistic term set	Five sites	Annual global horizontal irradiance, availability of water, distribution of hydrogen use sites, investment, maintenance cost, annual income, Photovoltaic hydrogen production potential, governmental and public support, demand for hydrogen, Energy-saving benefit, and carbon emission reduction
Wu et al. (2019)	China	Fuzzy Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) II	Five projects	Resource, infrastructure and construction, economy, environmental factors
Ayough et al. (2022)	Turkey	PROMETHEE and ISAW	five sites	Temperature, pressure, sunshine hour, slope, irradiation, public acceptance, distance from urban areas, and distance to transmission lines
Guo et al. (2021)	China	Hesitant fuzzy linguistic DEMATEL-PROMETHEE	Eight sites	Annual sunshine duration, wind speed, land availability, irradiation, temperature, precipitation, GDP, and population density
Agyekum et al. (2021)	Ghana	AHP- Density-based clustering	The whole country	Slope, land use, irradiation, distance from power lines and urban areas
Wang et al. (2022b)	Vietnam	Grey-DEA-TOPSIS	27 sites	Humidity, temperature, pressure, sunshine hour, precipitation, cloudiness, wind speed, skilled workforce availability, elevation, electricity demand, land acquisition, cost, and proximity to the road network and residential areas
Wang et al. (2021b)	Vietnam	DEA-AHP	20 sites	Humidity, temperature, pressure, sunshine hour, precipitation, cloudiness, wind speed, skilled workforce availability, elevation, electricity demand, land acquisition, cost, and proximity to the road network and residential areas
Wang et al. (2020)	Vietnam	DEA-FANP	Seven sites	Temperature, wind speed, sunshine hours, elevation, humidity, protection law, and economic and technological factors
Wang et al. (2023b)	Indonesia	DEA, F-AHP, F-MARCOS	32 provinces	Humidity, temperature, pressure, sunshine hour, precipitation, cloudiness, wind speed, skilled workforce availability, elevation, electricity demand, land acquisition, cost, and proximity to the road network and residential areas
Hassan et al. (2023b)	Saudi Arabia	CRITIC–TOPSIS	Three cities, namely, Al Ahsa, Dammam, and Abha	Humidity, temperature, pressure, sunshine hour, precipitation, wind speed, temperature and system losses, NPV, payback period, population density, and GHG emission saving
Qasimi et al. (2023)	Afghanistan	Genetic optimization algorithm-AHP	Nine states	Irradiation, slope, elevation, temperature, proximity to transmission lines, residential areas, and roads, aspect
Vagiona et al. (2022)	Greece	AHP-TOPSIS	Aegean Sea	Water depth, distance from shore, primary Voltage, distance to port, irradiation, installation area
Solangi et al. (2019)	Pakistan	AHP-fuzzy VIKOR	14 sites	Cost of land, infrastructural cost, operations and maintenance cost, electricity demand, flat terrain and without trees site, wildlife, and habitat, carbon emissions saving, public acceptance, employment opportunities, effect on the local economy, elevation, slope, and aspect
Anser et al. (2020)	Turkey	SWOT (strengths, weaknesses, opportunities, and threats) -based AHP–F-TOPSIS	seven cities	Impact on agriculture, employment, Outcome of the financial progress, general acceptance, distance from housing area, solar energy data accessibility, skilled workforce, climatic conditions, substructure cost, transmission grid accessibility, road accessibility, graphic impact, wildlife and endangered, sound impact, harmful toxin emission, public policies, supervisory boundaries, and acquisition of land
Lee et al. (2015)	Taiwan	DEA-FAHP	Five counties	Temperature, wind speed, sunshine hours, and elevation
Mian et al. (2023)	Saudi Arabia	FAHP-VIKOR	15 sites	Solar radiation, GHI, wind speed, sunshine hours, topography, population, sand and dust storm
Sánchez-Lozano et al. (2016)	Spain	TOPSIS-ELECTRE TRI	15 sites	Agrological capacity, slope, area, field orientation, distance to main roads, distance to power lines, distance to cities, distance to electricity transformer substations, and Potential solar radiation

Appendix 4. Fuzzy Delphi steps

The Fuzzy Delphi technique involves two crucial aspects: the Triangular Fuzzy Number and the Defuzzification process. The data analysis process commences by arranging the m1, m2, and m3 values to obtain the triangular fuzzy number. The minimum value is represented by m1, the reasonable value by m2, and the maximum by m3. A Triangular Fuzzy Number is applied to create the Fuzzy scale, which translates the linguistic variable to the fuzzy number. The Fuzzy scale follows odd numbers to express the level of agreement (Yao et al., 2022). Linguistic variables and equivalent fuzzy numbers, used by experts to validate the factors, are shown in Table A1.

A1. Linguistic variables

Linguistic variables	Triangular fuzzy numbers (l,m,u)
Strongly Disagree(SD)	$(0, 0, 0.1)$
Totally Disagree(TD)	$(0, 0.1, 0.3)$
Disagree(D)	$(0.1, 0.3, 0.5)$
Not Sure(NS)	$(0.3, 0.5, 0.7)$
Agree(A)	$(0.5, 0.7, 0.9)$
Totally Agree(TA)	$(0.7, 0.9, 1)$
Strongly Agree(SA)	$(0.9, 1, 1)$

Step 1 Initiate the process:

Designating a facilitator to guide the initiating of the Fuzzy Delphi process is recommended. This person should know the subject matter and be skilled in leading group discussions. The facilitator's role is to ensure that all participants have an equal opportunity to contribute their opinions and ideas and to keep the conversation focused and productive.

Step 2 Identify experts:

When considering a subject or topic, it is essential to identify and select experts with relevant knowledge and experience in that area. These experts can provide valuable insights, opinions, and recommendations based on their expertise. To identify these experts, conducting research, reviewing industry publications, attending conferences or events, or consulting with colleagues with connections in the field is possible.

Step 3 Define the problem:

In order to seek the insights and guidance of experts, it is essential to articulate clearly and precisely the specific problem or question that requires their opinions. This stage involves providing detailed context and background information, identifying relevant factors or variables, and framing the problem or question in a specific and actionable way. By doing so, the experts are equipped with all the necessary information to provide informed and valuable insights to make better decisions and achieve the goals.

Step 4 Round one questions:

During the initial round of gathering opinions from experts, it is important to ask open-ended questions that encourage them to express their thoughts freely. By doing so, a wide range of perspectives can be valuable in developing a comprehensive understanding of the matter. Open-ended questions allow experts to provide detailed responses, which can help to identify any potential biases or misunderstandings that may be present. Ultimately, this first round aims to gather as much information as possible to make informed decisions.

Step 5 Round two refinement:

After receiving the initial feedback from the experts in the first round, the next step is to analyze their responses and refine the questions accordingly. This refinement aims to make the questions more specific and focused so that the experts can provide a more detailed and informed opinion in the next round. Once the questions have been reviewed and improved, they will be presented to the experts again for a more targeted round of feedback. This iterative process of refining questions and gathering expert opinions will continue until a consensus is reached or until the desired level of insight has been obtained.

Step 6 Analysis using fuzzy logic:

When analyzing the responses provided by experts, it is essential to consider the inherent uncertainty and variability that can be present. To address this, one approach that can be utilized is fuzzy logic. Fuzzy logic allows for considering multiple possibilities or outcomes rather than relying solely on a binary approach of true or false. The following equations are used to aggregate the experts' opinions and defuzzification. Let $A_1 = (m_1, m_2, m_3)$ and $A_2 = (n_1, n_2, n_3)$ two fuzzy triangular numbers; therefore the equation E_1 is used to aggregate A_1 *and* A_2. Moreover, the equation E_2 is used for defuzzification(Ismail et al., 2019).

$$\overline{A} = (\min(m_1, n_1), m_2 \times n_2, \max(m_3, n_3)) \quad \text{E1}$$

$$Defuzzification(A_1) = \frac{m_1 + m_2 + m_3}{3} \quad \text{E2}$$

Appendix 5. PF-SWARA-COPRAS

Step 1 Let $A = \{A_1, A_2, \ldots, A_m\}$ a set of alternatives, $I = \{I_1, I_2, \ldots, I_n\}$ a set of indicators, and $E = \{E_1, E_2, \ldots, E_l\}$ a set of Decision Experts (DEs). The decision matrix (N) is expressed by $N = (a_{ij}^k), for\ i = i, \ldots, n; j = 1, \ldots, m;\ k = 1, \ldots, l$; where, a_{ij}^k shows the given support to alternative (i) concerning the indicator (j) by kth DE.

Step 2 Decision experts have different importance (weight), which should be calculated. To this end, E_3 is used.

$$\varpi_k = \frac{\acute{S}_k}{\sum_{k=1}^{l} \acute{S}_k} \quad \text{E3}$$

Where, $\sum_{k=1}^{l} \varpi_k = 1$.

Step 3 The individual decision matrices should be aggregated using PFWA. Let $Z = [z_{ij}]_{m\times n}$ The aggregated decision matrix; thus E_4:

$$Z = PFWA_{\varpi} = \left(1 - \prod_{k=1}^{l}\left(1-\mu_{ij}^{k}\right)^{\varpi_j}, \prod_{k=1}^{l}\left(\eta_{ij}^{k}\right)^{\varpi_j}, \prod_{k=1}^{l}\left(\eta_{ij}^{k} + \upsilon_{ij}^{k}\right)^{\varpi_j} - \prod_{k=1}^{l}\left(\eta_{ij}^{k}\right)^{\varpi_j}\right), for\ i = 1, \ldots, n; j = 1, \ldots, m. \quad \text{E4a}$$

Step 4 Indicators' weight should be calculated. To this end, the PF-SWARA is applied; its steps are presented below. It should be noted that decision experts support indicators directly in the SWARA method; thus, individual matrices should be aggregated using PFWA, like step 3. After aggregation, the following steps should be done,

Step 4.1 Crisp values are calculated using Equation E_4.

$$\acute{S} = \frac{\mu_\alpha + \eta_\alpha - \nu_\alpha + 1}{2} \quad \text{E4b}$$

Step 4.2 Indicators are ordered from the most to the least essential indicator concerning DEs' preferences.

Step 4.3 The indicators' significance is compared with the first preferred indicator and their differences (c_j) are calculated.

Step 4.4 The comparative coefficient k_j is calculated using E_5. The difference between j and j-1 indicates the successive comparative significance.

$$k_j = \begin{cases} 1 & j = 1 \\ \acute{s}_j + 1 & j > 1 \end{cases} \quad \text{E5}$$

Step 4.5 The indicators' importance p_j is calculated using E_6.

$$p_j = \begin{cases} 1 & j = 1 \\ \frac{p_{j-1}}{k_j} & j > 1 \end{cases} \quad \text{E6}$$

Step 4.6 The weight of normalized indicators is calculated using E_7.

$$w_j = \frac{p_j}{\sum_{j=1}^{n} p_j} \quad \text{E7}$$

Step 5 The weighted decision matrix $\overline{Z} = [\overline{z}_{ij}]_{m\times n}$ is constructed using E_8 after calculating the indicators' weight using the SWARA.

$$\overline{Z} = z_{ij} \times w_j, for\ i = 1, \ldots, m; j = 1, \ldots, n \quad \text{E8}$$

Step 6 Values of indicators are summed using E_9 and E_{10} for benefits and costs.

$$R_i^+ = \sum_{j=1}^{n} \overline{z}_{ij}{}^{+} = \left(1 - \prod_{i=1}^{n} 1 - \mu_{\overline{z}_{ij}{}^{+}}, \prod_{i=1}^{n} \eta_{\overline{z}_{ij}{}^{+}}, \prod_{i=1}^{n}\left(\eta_{\overline{z}_{ij}{}^{+}} + \nu_{\overline{z}_{ij}{}^{+}}\right) - \prod_{i=1}^{n} \eta_{\overline{z}_{ij}{}^{+}}\right) \quad \text{E9}$$

$$R_i^- = \sum_{j=1}^{n} \overline{z}_{ij}{}^{-} = \left(1 - \prod_{i=1}^{n}\left(1 - \mu_{\overline{z}_{ij}{}^{-}}\right), \prod_{i=1}^{n} \eta_{\overline{z}_{ij}{}^{-}}, \prod_{i=1}^{n}\left(\eta_{\overline{z}_{ij}{}^{-}} + \nu_{\overline{z}_{ij}{}^{-}}\right) - \prod_{i=1}^{n} \eta_{\overline{z}_{ij}{}^{-}}\right) \quad \text{E10}$$

Step 6 The final ranks of alternatives are calculated using E_{11}.

$$\mathbb{C}_i = \acute{S}\left(R_i^+\right) + \frac{\sum_{i=1}^{m} \acute{S}\left(R_i^-\right)}{\acute{S}\left(R_i^-\right) \sum_{i=1}^{m} \frac{1}{\acute{S}\left(R_i^-\right)}} \quad \text{E11}$$

Step 7 The utility degrees are calculated using E_{12}.

$$U_i = \frac{\mathbb{C}_i}{\mathbb{C}_{max}} \times 100 \ \ for\ i = 1, \ldots, m \tag{E12}$$

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NOTES

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