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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.

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 policymakers 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.

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

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

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

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

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

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

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 $IFWA^{\varepsilon}_{\omega}$.

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

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 kth 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.

$$PIS = \left\{ \left(\max_i Nor.Value_{ij} | j \in J \right), \left(\min_i Nor.Value_{ij} | j \in J' \right) | \ i = 1, \ldots, \ m \right\} = \left\{ PIS_1^+, \ PIS_2^+, \ \ldots, \ PIS_n^+ \right\} \tag{13}$$

$$NIS = \left\{ \left(\min_i Nor.Value_{ij} | j \in J \right), \left(\max_i Nor.Value_{ij} | j \in J' \right) | \ i = 1, \ldots, \ m \right\} = \left\{ NIS_1^-, \ NIS_2^-, \ \ldots, \ NIS_n^- \right\} \tag{14}$$

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.

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

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

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

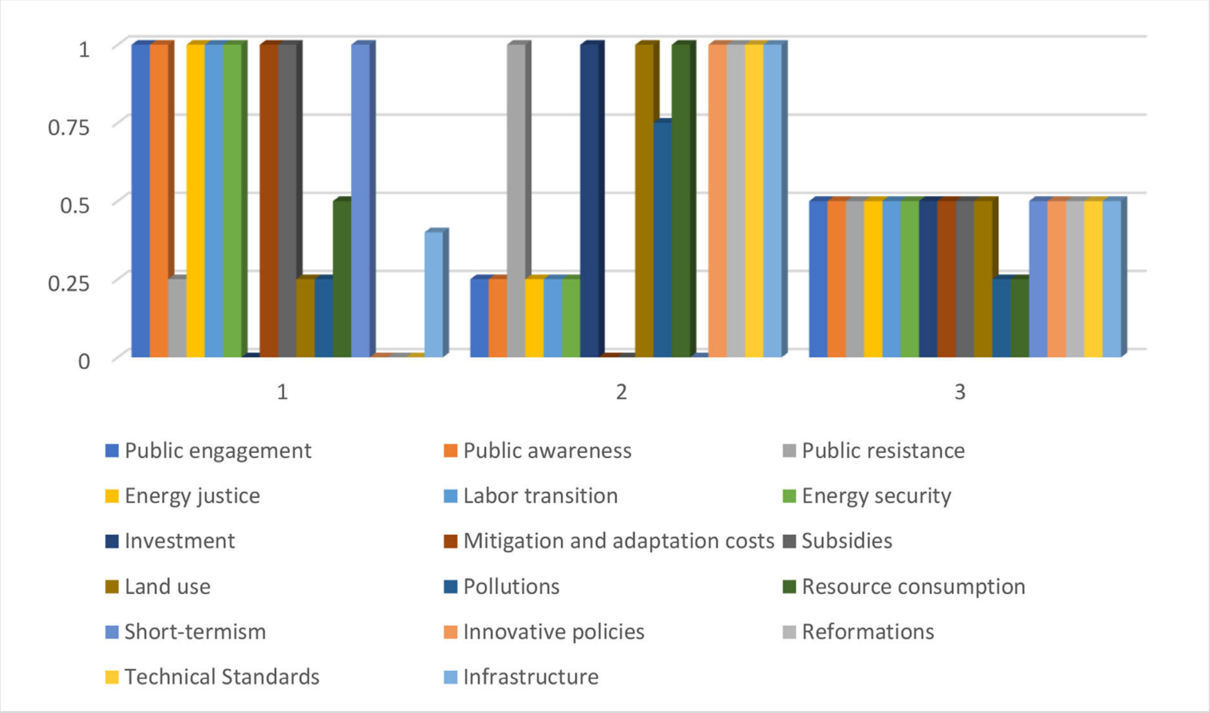

Figure 1. Initial values for running scenarios on FCMapper vs. 1

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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