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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 policymaking, 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 reskilled 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 break-even 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.

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

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

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

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

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 $\zeta_2 = (\alpha_{\zeta_2}, \beta_{\zeta_2})$.

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

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

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

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

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

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

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$^{\text{th}}$ 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 $\text{A} = (a_i)_m$ 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.

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

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.

$$\Lambda_i = \begin{cases} 1 i = 1 \\ \overset{\prime}{s_i} + 1 i > 1 \end{cases} \tag{13}$$

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 $\Xi = \left(z_{tj}\right)_{t \times j}, \forall t = 1, \ldots, y; j = 1, \ldots, n;$ 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 $\left\{A_1, A_2, \ldots, A_y\right\}$.

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

Step 2 Normalization

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

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

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

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

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.

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

Step 3.1 Positive and negative ideal solutions

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

$$A^+ = \left\{\left(\max_t \upsilon_{tj} | j \in J\right), \left(\min_t \upsilon_{tj} | j \in J'\right) | i = 1, \ldots, m\right\} = \left\{v_1^+, v_2^+, \ldots, v_n^+\right\} \tag{24}$$

$$A^- = \left\{\left(\min_t \upsilon_{tj} | j \in J\right), \left(\max_t \upsilon_{tj} | j \in J'\right) | i = 1, \ldots, m\right\} == \left\{v_1^-, v_2^-, \ldots, v_n^-\right\} \tag{25}$$

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).

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

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

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.

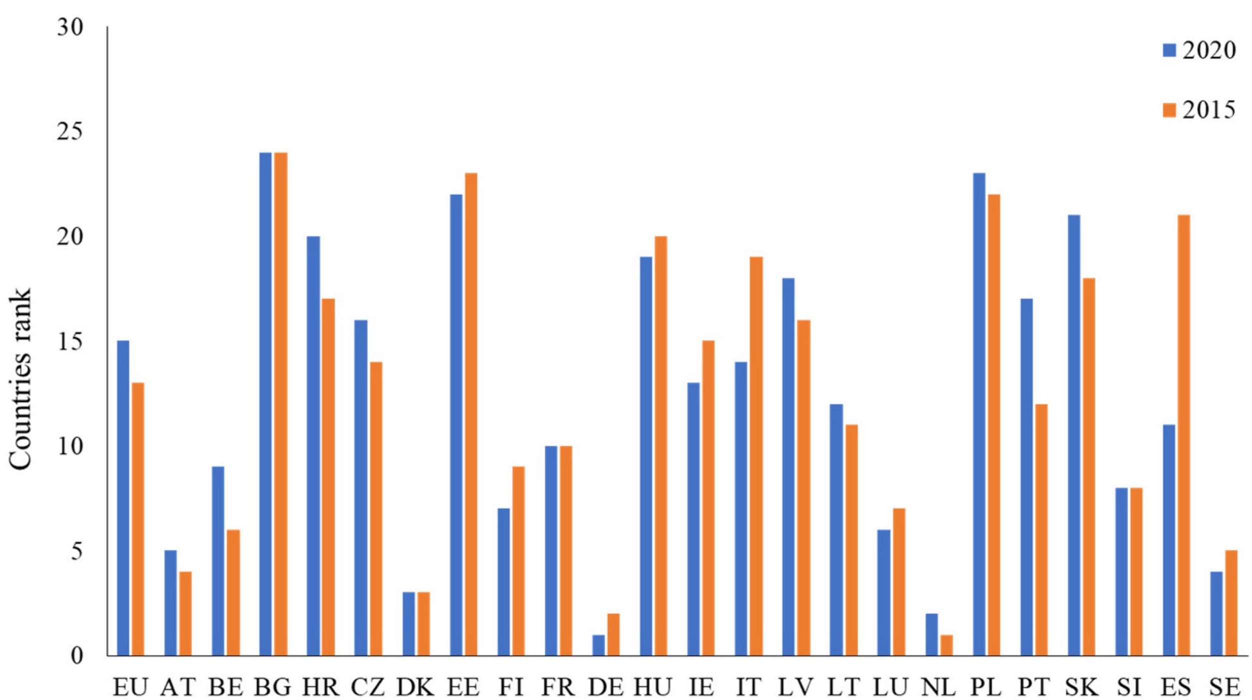

Fig. 1 Ranks of the EU countries according to their performances in dealing with the identified challenges of low-carbon energy transition

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

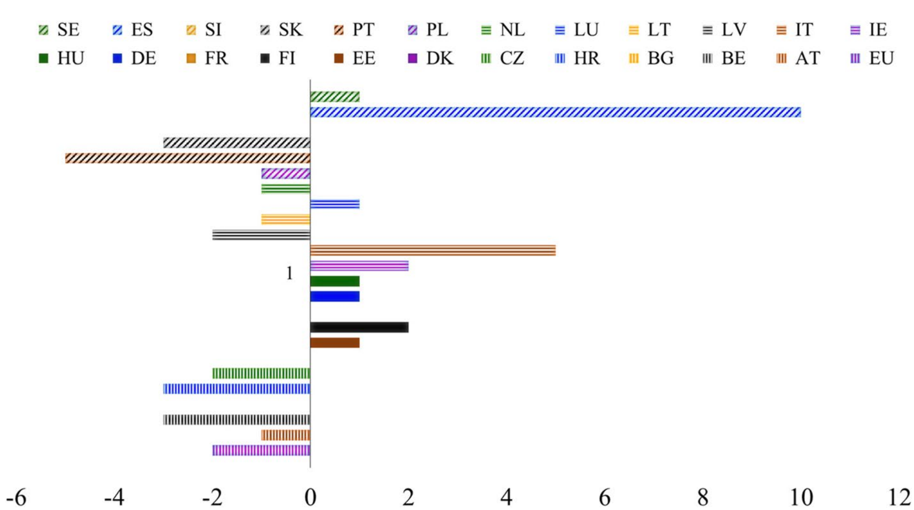

Fig. 2 Changes in the EU countries' ranks over the five years from 2015 to 2020- positive changes show growth in countries' ranks, while negative changes show the opposite, and zero means no change over the years

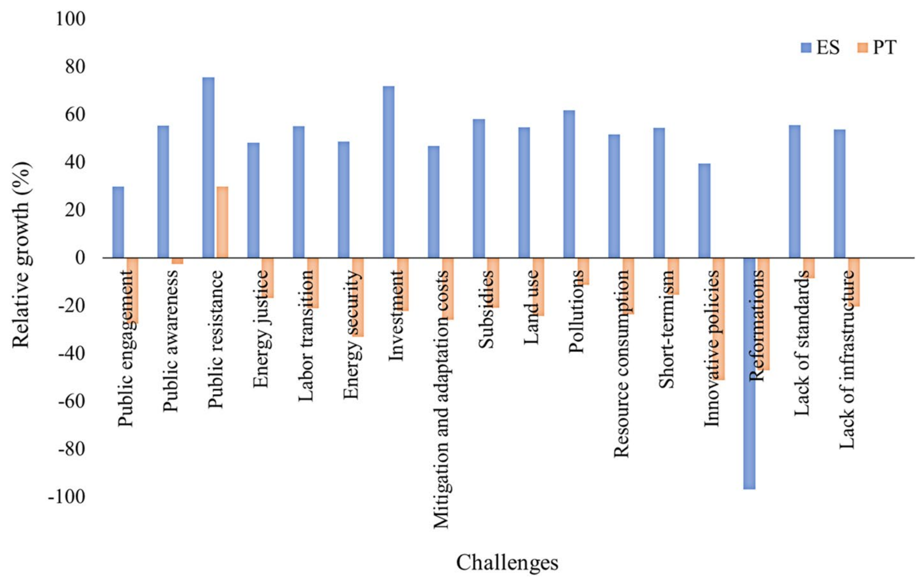

Fig. 3 Growth by focused challenges for Spain and Portugal, which had the highest and lowest relative growth over the five years from 2015 to 2020 in the EU

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

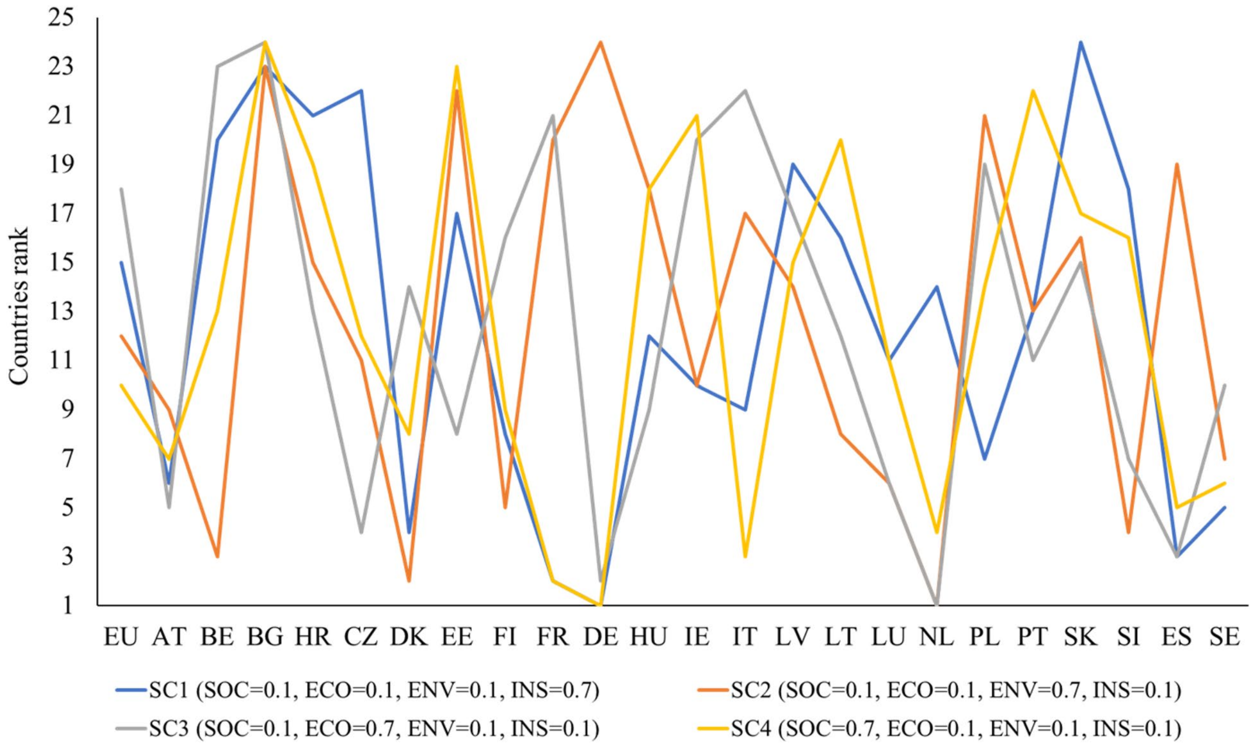

Fig. 4 Sensitivity analysis results under four scenarios for all the EU countries, showing how fluctuating ranks could be under various assumptions

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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Authors' contributions
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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Availability of data and materials
Data are available at https://www.iea.org and https://ec.europa.eu/eurostat/data/database.

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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