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Supporting Europe's Energy Policy Towards a Decarbonised Energy System: A Comparative Assessment

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Abstract: The European Union (EU) aims to prepare its strategy and infrastructure for further decarbonisation of its energy system in the longer term towards 2050. Recent political discussions and research interest focus on ways to accelerate the development and deployment of low-carbon technologies with respect to the targets set for 2030 and 2050. However, the diverse options available that are to be implemented, are policy sensitive and need careful comparative assessment. This paper presents a multi-criteria approach based on an extension of the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) method for group decision-making that incorporates fuzzy set theory in order to evaluate alternative transformation pathways for achieving a sustainable energy system in EU. This assessment aims at providing a direction towards a most preferable pathway concept that should be taken into account by a future model-based analysis of the necessary transformation of our energy sector. The results obtained could support policymakers in drawing effective recommendations based on the findings. The added value of this analysis to policymakers is its contribution to plan climate and energy strategies towards a low-carbon transition pathway by using the information of this approach and prioritizing uncertainties through an environmental and energy perspective.

Keywords: climate and energy policy; transformation pathways; low carbon technologies; decision support; multi-criteria analysis; fuzzy PROMETHEE

1. Introduction

In these days, as the impact of climate change becomes more and more prevailing, formulation of mitigation policies has become a high priority on Europe's political agenda. Through the "2030 Climate and Energy Policy Framework", more binding targets were defined for 2030 requiring: at least 40% cuts in greenhouse gas emissions (from 1990 levels), at least 27% share for renewable energy and at least 27% improvement in energy efficiency [1], while recently the European Parliament approved binding 2030 target for renewables (32%) and an indicative target on energy efficiency (32.5%) that will play a crucial role in meeting the European Union's (EU) climate goals [2]. For the more distant future, based on the EU Energy Roadmap 2050 the focus lies in four main decarbonisation routes for the energy sector, which are mainly focused on: energy efficiency measures, renewable energy sources (RES), nuclear and carbon, capture and storage (CCS) [3]. The EU is now on a path towards a low carbon economy by 2050, to ensure regulatory certainty and a sustainable energy future [4]. In this concept and in order to promote technology in EU's energy and climate policies, the Strategic Energy

Technology Plan (SET-Plan) was designed in 2008 [5]. Since then, it has been EU's key pillar to address the challenge of accelerating the development of low-carbon technologies, which ultimately aims at widespread adoption by the market.

Although targets are well defined, extensive uncertainties exist in the European energy future necessitating the identification and analysis the parameters affecting the proposed decarbonisation options. Scenarios are a widely used tool for analysing the unknown future and they have been widely exploited in the field of climate change adaptation and policy [6,7]. Scenarios are defined as "alternative images of how the future might unfold" [8] or in other words, "plausible descriptions of how the future might evolve, based on a coherent and internally consistent set of assumptions ('scenario logic') about the key relationships and driving forces" [9]. Literature review greatly manifests that there is a variety of perspectives regarding critical uncertainties affecting the energy future. Ghanadan and Koomey (2005) [10] in their publication underline five major driving forces, namely the relevance of energy diversity, relative attention to oil and transportation, long-term prominence of energy and security, types of clean energy activities, and role of distributed generation, while Kowalski et al. (2009) [11] differentiates scenarios based on the technologies exploited. Brown et al. (2001) [12] use the levels of action or cost of each policy as guidelines to develop policy scenarios. Raskin et al. (2010) [13] first consider the extent to which scenarios emerge from the turbulence of the present or emerge gradually as evolutionary futures and second, they assess the prioritization of sustainable development. Through scenario formulation Riahi et al. (2012) [14] put more emphasis on energy efficiency and demand-side transformation, and they name three key uncertainties: the level of energy demand, fuels and technologies in the transportation section, and differentiation of portfolio option from supply-side.

Using as a compass the principle that the objective of using scenarios is not to predict the future, but to better understand uncertainties in order to reach decisions that are robust under a wide range of possible futures [15], this paper focuses on two critical uncertainties in order, not to forecast the state of the global energy system by the year 2050, but rather bound the range of plausible alternative futures by defining certain trajectories that could significantly affect decarbonisation policy in the years to come. More precisely, in this analysis the widely-used 2x2 scenario typology adopted so as to combine two main dimensions of uncertainty into four storylines spanning a wide possibility space. Figure 1 indicates the scenario topology that varies two critical uncertainties: decentralisation vs. path dependency (x-axis); and cooperation vs. entrenchment (y-axis). On the x-axis is the degree of decentralization that focuses on whether variation and experimentation of energy policies is being pursued or whether minimal switching and transitional costs are sought. On the y-axis is the degree of European cooperation that explores whether there is centralized coordination or control at national level. These two dimensions of uncertainty create a possibility space that could be explored by the four contrasting storylines that generate four different transformation pathways, the key characteristics of which will be presented in the following study.

This paper analyses the aforementioned transformation pathways on the basis of a set of relevant criteria aiming at revealing the one with the most auspicious prospects of succeeding and achieving energy sustainability in EU. To deal with the disparate preferences of decision-makers, as well as to manage the uncertainty that arises when solving decision problems, a methodological assessment framework is developed using the multi-criteria Fuzzy Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) method, which combines the principles of multi-criteria decision analysis and fuzzy logic. The results provide a clear picture of the preferred options and their interactions with the evaluation criteria, while the conclusions can significantly contribute to energy and climate policy-making in the energy sector.

Due to its ability to deal with ranking of many alternatives based on conflicting criteria, multi-criteria analysis has been one of the very fast-growing areas of Operational Research during the two last decades, with applications in various areas of human activity [16]. Many strategic environmental and energy planning issues have been analysed based on multi-criteria decision-making

(MCDM) methods [17–26] and especially the use of PROMETHEE method has concentrated great interest as it becomes apparent after an extensive literature review [27–35].

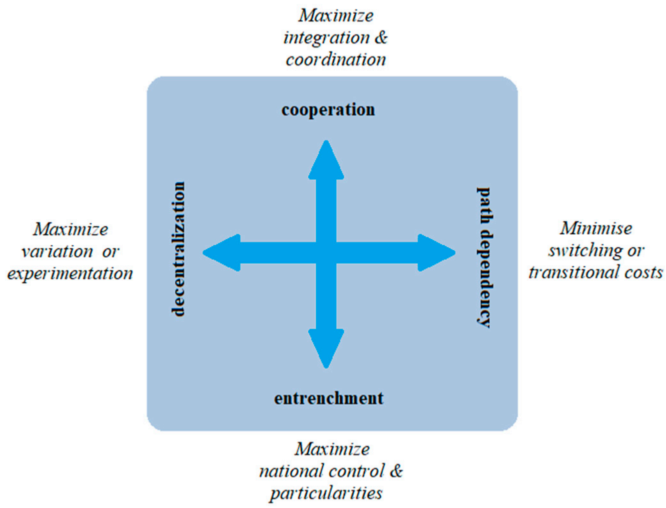

Figure 1. Proposed 2 × 2 scenario topology.

In order to meet specific requirements when uncertain and imprecise knowledge, as well as possibly vague preferences have to be considered [36], fuzzy set theory is integrated in the proposed methodological framework. From 2000 to 2017, fuzzy PROMETHEE has been exploited in at least twenty-five publications [37] and according to Kahraman et al. (2015) [38] some of the most impactful articles tackle problems in the environmental management field [39–41]. Making use of the popularity and suitability of fuzzy PROMETHEE in managing energy sector problems and the restricted number of fuzzy PROMETHEE publications for evaluating different energy futures, this study offers an original work able to shed light in the policy-making problem related to sustainable transition. To the best of our knowledge, however, this is the first fuzzy-PROMETHEE-based MCDM technique for group decision-making developed for ranking transformation pathways for achieving a sustainable European energy future. In doing so, we attempt to extend the application domains of the fuzzy PROMETHEE method. The added value of this analysis to policymakers is its contribution to plan climate and energy strategies towards a low-carbon transition pathway by using the information of this approach and prioritizing uncertainties through an environmental and energy perspective.

Following this introductory section, the remainder of the paper is structured as follows: The second section provides an overview of the material and methods that were followed for the comparative assessment of the transformation pathways towards a decarbonised energy system. It starts with an overview of the methodological approach that were followed. In the Problem formulation subsection, the alternative transformation pathways are elaborated and the evaluation criteria are presented. In the next subsection, the appropriate MCDM method is selected after an extended review in the field of multi-criteria analysis and energy policy planning. The choice of method is justified, fuzzy set theory is presented briefly and the main steps for implementing the fuzzy PROMETHEE are described. Subsequently, the methodology is applied in the Results section and the produced output is analysed in the Discussion section. Finally, in the Conclusions section, the main conclusions are summarized and key points are proposed for further research.

2. Materials and Methods

2.1. Overview of the Methodological Approach

The following Figure illustrates the methodology applied to assess the suitability and effectiveness of alternative transformation pathways to achieve the transition towards a sustainable European energy future (Figure 2).

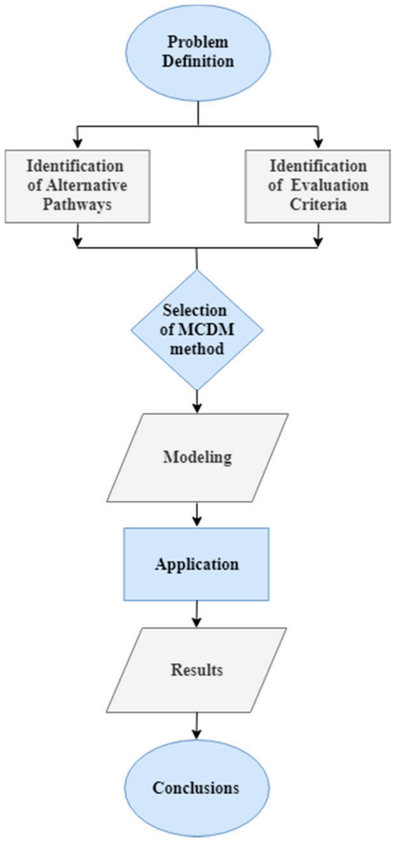

Figure 2. Overview of the methodological approach.

The first step was the definition of the problem, which involved the identification of alternative transformation pathways, which reflect different sustainable trajectories for the European energy future, and identification of criteria for their evaluation (Section 2.2). Subsequently, after taking into consideration the specific characteristics of the problem under study and the corresponding literature (Sections 2.3.1–2.3.3), and after a detailed comparison among the MCDM methods (Section 2.3.4), the most appropriate MCDM method was selected. This MCDM method was applied to compare and rank the alternatives from the most to the least preferable according to decision-makers' value system. Therefore, after gathering all necessary information about pathways' ratings and defining method's parameters, the selected MCDM algorithm was executed multiple times for sensitivity analysis purposes (Section 2.3.5). Finally, the resulting rankings were analysed providing valuable insight regarding the most suitable pathways for achieving decarbonisation in EU (Sections 4 and 5).

2.2. *Problem Formulation*

2.2.1. Alternative Transformation Pathways

First, alternative transformation pathways for achieving a sustainable transformation of the EU energy system are defined. The pathways formulation is based on research conducted within the framework of the "SET-Nav - Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation" project (http://set-nav.eu/). The four narratives presented below stem from the 2x2 topology described in Introduction and they are formulated with the aim to answer questions regarding: (a) driver questions related on '*why*' the pathway scenario happens and (b) elements questions highlighting '*what happens*' with focus on the outcome of the pathways [42]. Their key characteristics are described in this section and Figure 3 summarizes schematically the four alternatives.

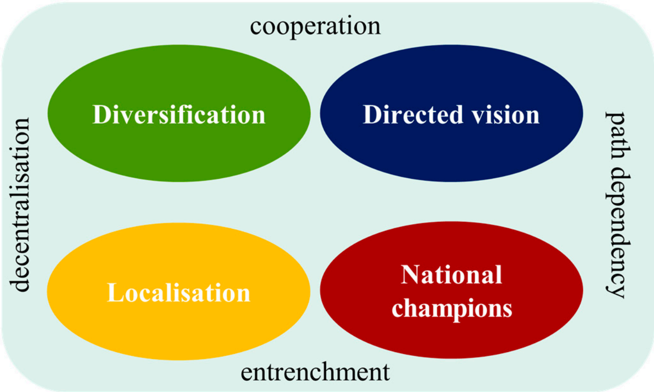

Figure 3. Transformation pathways at a glance [42].

A$_1$—Diversification**.** This pathway describes a decentralizing trajectory for the EU energy system in the context of cross-border cooperation and integration. This signals the entry of new, heterogeneous actors, challenging the dominance of centralised asset-owners and incumbent service-providers. Open digital platforms become essential for coordinating the activity of this diversified energy economy, facilitated by regulatory experimentation and opening. This provides a positive environment to foster interaction among heterogeneous actors across countries. Active involvement of consumers and developments in digitalization allows smart grid technologies to thrive as well as to setup opportunities for new entrants and innovation. In this pathway, renewable energies, smart grids and electrical vehicles are the driving force behind decarbonisation. Countries have cooperative attitudes towards regulatory opening and promoting new business models. This path requires cooperation between countries on technological progress, diversification of flexibility options for balancing RES and modest expansion of interconnected electricity grid capacity.

A$_2$—Directed Vision**.** This storyline defines a path-dependent trajectory for the EU energy system that is directed by the Commission's vision set out above for an ever-closer energy union. The EU together with stakeholders (able to operate at an EU level) is guided by strong and shared expectations for future goals and current directions of travel. This broad buy-in becomes enshrined in stable policy frameworks which are coordinated between member states to ensure a consistent European-wide playing field. For this pathway cooperation is expected between member states on technological progress matters. Within this pathway we expect a balanced mix in energy supply, comprising new nuclear fleet (but no prolongation of the existing one), CCS and renewables with focus on centralised solutions as key pillars. A diversification comes into play for flexibility options to facilitate RES integration but with prioritisation of centralised solutions. Concerning infrastructure, we expect a strong expansion in grid capacity whereas energy efficiency remains as no regret option.

A$_3$—National Champions**.** This pathway defines a path-dependent EU in which historical incumbency and national interests play a stronger guiding hand. This continuity in development minimises transitional risks and costs, at least in the near-term. Incumbent firms and organisations, including current or former national monopolies, play a leading role particularly in the design, finance, construction and operation of large-scale energy infrastructure. This pathway assumes a focus on national preferences, using available resources and prioritising tailored solutions according to national needs. Incumbents in the energy sector have a decisive role in defining national policy priorities. The focus on what is there nationally/locally leads in energy supply to the prolongation of the operational times of nuclear (existing fleet) that goes hand in hand with the built-up of new capacities, CCS plays a strong role, and (centralised) renewables contribute depending on their local availability. Grid expansion is moderate and energy efficiency remains as no regret option.

A$_4$—Localisation. This storyline describes how the decentralising forces observable today in the EU start to chip away more forcefully at the centralised infrastructures, firms, and regulatory environments, but with marked national and local variation. Member states seek to maximise their use of locally-available resources, giving rise to differentiated energy strategies and policy frameworks across the EU. Resistance to pan-European infrastructure and integration projects opens up space for smaller-scale experimentation and diversity. Digitalisation again becomes essential for supporting coordination and effective system management, but with an emphasis on national competitive advantage in the returns to scale of a dominant platform. In accordance with above-mentioned, there is a clear focus on local resources and solutions. Moreover, there is a clear ban for large scale international cooperation, being on regulation as well as on infrastructure (grids). That puts in practice a limit for centralised supply solutions, with only exceptions possible at country level. The focus on what is there nationally/locally available leads to the prolongation of the operational times of the existing nuclear fleet, while CCS may play a role locally and renewables contribute depending on their local availability with a tendency towards decentral/local options due to the lack of grid interconnection. Grid expansion is very limited and energy efficiency remains as no regret option.

It is crucial to underline that these short descriptions highlight only the most salient features that support separate the storylines from one another. Interpreting each storyline is not an exact science. However, it is essential that the interpretive detail of each storyline is internally consistent (avoiding tensions or contradictions), comprehensive (covers all relevant drivers and dynamics), and coherent (adds up to a meaningful whole).

2.2.2. Evaluation Criteria

The existence of different possible trajectories for the European energy future necessitates their comparative assessment based on a well-defined and representative set of criteria in order to distinguish the most propitious one. Given the available pathway narratives, the following four criteria were defined with a view to capture and encompass all key features of the alternatives into the evaluation process. It is worth mentioning that the definition process of the of the assessment criteria, as well as their final section were assisted and validated by the integration of experts' insights and opinions, harvested through a participatory process [43]. This process was elaborated through a series of bilateral meetings with stakeholders and facilitated by the implementation of topical and modelling workshops with the framework of the EU Horizon2020 SET-Nav project, fostering dialogue in order to gain useful feedback on the most suitable criteria.

C_1—Regulatory Framework. This criterion assesses the adequacy of the regulatory framework to support and ensure the implementation of the actions and policies proposed by each path. The more relaxed the legislative framework, the greater the risk of failure in the implementation of the planned policies, and the more amendments it requires, the more difficult it becomes to implement [44].

C_2—Compatibility with Market. Given that Europe has a mature market, it is important to assess the extent to which each pathway is compatible with the current situation or if it opposes it because its actions involve changes in consumer behaviour and the role of the participating companies in energy market, thus leading to a change in demand and price equilibrium. In the light of this criterion, the pathways requiring a mature market are more preferable due to their easier application in the present mature environment, while the rest are considered more prone to risk as they require significant changes [45,46].

C_3—Compliance with SET-Plan. This criterion reflects the extent to which each pathway achieves the goals of SET-Plan and evaluates its ease of implementation. Ease of implementation lies in the volume of new infrastructures and technologies included paths. The more complex and innovative policies are, the more difficult it is to implement them, since they deviate from the existing reality and therefore have a greater risk of failure [5].

C_4—Stakeholder Awareness. This criterion assesses the extent to which those involved in each path are aware of climate change issues and are actively taking action to combat it. The term "stakeholders" refers to the European Union, the Member States, associated enterprises and the society. The greater the familiarity with greenhouse gas reduction mechanisms, the more auspicious the prospects for the success of the actions each pathway proposes [47].

2.3. Selection of the MCDM Method

2.3.1. The PROMETHEE Method

According to Siskos (2008) [48], the difficulty or the complexity of a decision problem should be sought mainly in two factors: firstly, to the multidimensional character of the alternatives' consequences and secondly, to the uncertainty that governs the problem's data. The methodological framework that is widely used to tackle such problems is offered by MCDM approaches. Apart from their obvious ability to handle numerous criteria, these methods also facilitate the decision-maker to better understand the problem's nature and prioritize criteria, and hence they promote decision-makers' active engagement with the process and support collective decision-making [26]. Hence, the transformation pathways evaluation problem clearly belongs to the category of such complex problems which calls for a multi-criteria approach.

In this study, the PROMETHEE method was selected due to its simplicity and its capacity to approximate the way human mind expresses and synthesizes preferences in front of multiple contradictory decision perspectives [49]. The PROMETHEE it was initially developed by Brans in 1982 [50], further extended by Vincke & Brans (1985) [51] and belongs to the family of MCDM methods that rely on the outranking relations theory. It is based on pairwise comparisons between two alternative choices in order to determine partial binary relations denoting the strength of preference of an alternative A over alternative B, and the final ranking results from taking into account the degree of superiority (Leaving Flow) and inferiority (Entering Flow) that each alternative has compared to the others.

The PROMETHEE family of outranking methods includes the PROMETHEE I for partial ranking of the alternatives and the PROMETHEE II for complete ranking of the alternatives. There are also several alternative versions of the PROMETHEE methods, such as the PROMETHEE III for ranking based on interval, the PROMETHEE IV for complete or partial ranking of the alternatives when the set of viable solutions is continuous, the PROMETHEE V for problems with segmentation constraints [52], the PROMETHEE VI for the human brain representation [53] and the PROMETHEE Group Decision Support System (GDSS) for group decision-making [54].

When comparing different outranking methods, PROMETHEE stands out due to its fairly simple design, ease of computation and application and stability of results [35]. Some of the main advantages that the PROMETHEE method offers is that compensations between criteria can be controlled, less effort is required from the decision-makers for preference modelling, while the process enables them to stay closer to the actual decision problem. Apart from the methodological advantages, real life observations show that decision-makers are often not fully aware of their preferences, or that they are not able to express these in an unambiguous way without appropriate support and PROMETHEE method can provide this [35]. The advantage of the partial ranking of PROMETHEE I is that some bad performing alternatives can be excluded from the further evaluation exercises, with the consequence that the data requirement is reduced [55], while the complete ranking of PROMETHEE II is useful to supply to the decision-maker information on how the final ranking changes when different decisions on weights, criteria and aggregation procedures are taken [56]. PROMETHEE can simultaneously deal with qualitative and quantitative criteria, criteria scores can be expressed in their own units, while it can deal with uncertain and fuzzy information. Apart from the above-mentioned advantages and the recognition of the method, the selection of PROMETHEE was also stimulated by the availability of its methodological extensions in the fuzzy environment, facilitating the prospective enhancement of the tool, as well as its capacity to effectively tackle the problematic of interest, which is ranking the alternatives. According to Gavade (2014) [57], a limitation of PROMETHEE is that suffers from the rank reversal problem when a new alternative is introduced while, in the case of many criteria and options, it may become difficult for the decision-maker to obtain a clear view of the problem and to evaluate the results. However, this drawback does not affect the present problem since the number of the criteria and alternatives are limited.

2.3.2. Literature Review on PROMETHEE and Energy Policy

The MCDM methods of PROMETHEE family, as well as combination of the PROMETHEE with other MCDM techniques have been extensively applied to support decision-making processes for issues related to the energy policy, management and planning. Strantzali et al. (2017) [58] uses a multi-criteria decision-making model based on PROMETHEE II, to determine the best fuel mix for electricity generation in an isolated Greek island, having determined a set of 7 energy policy scenarios that are assessed against economic, technical, environmental and social criteria. The energy policy scenarios include the use of conventional fuels, wind energy and natural gas, in its liquid form, liquefied natural gas (LNG). A combination of the PROMETHEE method with the AHP was used by Turcksin et al. (2011) [59] to recommend a multi-instrumentality policy package to the Belgian government in its objective to reduce environmental externalities by encouraging people to make a more sustainable vehicle choice. Through PROMETHEE II Diakoulaki et al. (2007) [60] investigated the prospects for the exploitation of the Kyoto Protocol's Clean Development Mechanism (CDM) in Greece. The most promising types of CDM projects were evaluated in 5 selected host-countries in terms of technical experience, duration of project realization, legislative framework, political compatibility and emission reduction potential. In the same year Diakoulaki & Karangelis (2007) [61] employed PROMETHHE, based on economical, technical, and environmental criteria, to comparatively evaluate four scenarios for the development of the power generation sector in Greece. Doukas et al. (2006) [62] applied PROMETHEE II to evaluate the sustainable technologies for electricity generation, according to the environmental, social, economic, and technological dimension of sustainable development. Madlener et al. (2007) [63] used PROMETHEE algorithm to assess five renewable energy scenarios considered refer to Austria in the year 2020. The innovative methodology applied, examined possible energy futures paths by combining scenario development; multi-criteria evaluation; and a participatory process with stakeholders and energy experts on the national level.

Table 1 includes a variety of studies using PROMETHEE in energy related fields and environmental management [28,64,65].

Table 1. Literature review of PROMETHEE application in energy and environment sectors.

Studies	Application Area
Beynon & Wells, 2008; Kapepula et al., 2007; Linkov et al., 2006; Palma et al., 2007 [66–69]	Environmental Impact Assessment
Cavallaro, 2009; Diakoulaki & Karangelis, 2007; Doukas et al., 2006; 2008, Ghafghazi et al., 2010; Goumas & Lygerou, 2000; Haralambopoulos & Polatidis, 2003; Ren et al., 2009; Pohekar and Ramachandran, 2004; Tsoutsos et al., 2009 [39,61,62,70–76]	Selection & Assessment of Sustainable and Environmental Friendly Technological Options for Energy Generation
Diakoulaki et al., 2007, Vaillancourt & Waaub, 2004 [60,77]	Monitoring GHG Reduction Potential in a Country Level
Geldermann & Rentz, 2005, Mergias et al., 2007	Life Cycle Analysis
Queiruga et al., 2008, Vego et al., 2008 [55,78–80]	Waste Management
Hyde et al. (2003); Madlener and Stagl (2005) [81,82]	Ranking renewable energy technologies and scenarios

2.3.3. MCDM and Fuzzy Set Theory

The questions arising from the aforementioned criteria and which decision-makers are called upon to answer lead to qualitative input data that cannot be determined with a reasonable degree of accuracy. Therefore, fuzzy numbers appear as a more appropriate choice compared to crisp ones, since they can depict data from a more realistic approach [83–86].

The idea of incorporating fuzzy logic into MCDM methods has long being studied in the literature. Especially, in the case of outranking methods, which rely on pair wise comparisons and exploit the notion of preference and indifference, fuzzy logic is interweaved in the methods. As Chen et al. (2010) [87] put it, most outranking methods are based on a fuzzy notion since the comparisons do not hold true with the two-value logic (true/false).

The framework of fuzzy sets offers a simple way of handling problems in which the source of imprecision is the absence of sharply defined criteria of class membership (vagueness) rather than the presence of random variables [88]. In this respect, fuzzy set theory permits the gradual assessment of the membership of elements in a set; this is described with the aid of a membership function valued in the real unit interval [0, 1] [34]. In fuzzy applications, triangular fuzzy numbers (TFN), a special case of a trapezoidal fuzzy number, are widely exploited. According to the definition by Van Laarhoven and Pedrycz (1983) [89], a TFN is characterized by the following properties.

A fuzzy number $\widetilde{A}$ on X is a TFN if its membership function $\mu_{\widetilde{A}}(\chi)$: X→ [0, 1] equals

$$\mu_{\widetilde{A}}(\chi) = \begin{cases} \frac{x-l}{m-l}, & | \, l \le x \le m \\ \frac{u-x}{u-m}, & | \, m \le x \le u \\ 0, & elsewhere \end{cases} \quad (1)$$

where l and u are for the lower and upper bounds of fuzzy number $\widetilde{A}$, respectively, and m is median value.

A triangular fuzzy number is denoted as $\widetilde{N} = (l, m, u)$. Four basic arithmetic operations of triangular fuzzy numbers are listed below, as defined by Kaufmann and Gupta (1991) [90]:

Let $\widetilde{N}_1 = (l_1, m_1, u_1)$ και $\widetilde{N}_2 = (l_2, m_2, u_2)$.

i. Addition (+):

$$\begin{aligned} \widetilde{N}_1(+)\widetilde{N}_2 &= (l_1, m_1, u_1)(+)(l_2, m_2, u_2) \\ &= (l_1 + l_2, m_1 + m_2, u_1 + u_2)) \end{aligned}$$

ii. Subtraction (-):

$$\begin{aligned} \widetilde{N}_1(-)\widetilde{N}_2 &= (l_1, m_1, u_1)(-)(l_2, m_2, u_2) \\ &= (l_1 - l_2, m_1 - m_2, u_1 - u_2)) \end{aligned}$$

iii. Multiplication (×):

$$\begin{aligned} \widetilde{N}_1(\times)\widetilde{N}_2 &= (l_1, m_1, u_1)(\times)(l_2, m_2, u_2) \\ &= (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2)) \end{aligned}$$

iv. Division (/):

$$\begin{aligned} \widetilde{N}_1(/)\widetilde{N}_2 &= (l_1, m_1, u_1)(/)(l_2, m_2, u_2) \\ &= (l_1/l_2, m_1/m_2, u_1/u_2)) \end{aligned}$$

Notes:

- It is worth noting that $\widetilde{N}$ (−) $\widetilde{N}$ ≠ 0, $\widetilde{N}$ (/) $\widetilde{N}$ ≠ 1, where 0,1 depict fuzzy numbers (0, 0, 0) and (1, 1, 1), respectively. Therefore, solution $\widetilde{N}$ of the fuzzy equation $\widetilde{N}_2 = \widetilde{N}$ (–) $\widetilde{N}_1$ is not, contrary to what is expected, equal to $\widetilde{N} = \widetilde{N}_1$ (+) $\widetilde{N}_2$ [91].
- Notably, the computational results of multiplication (iii) and division (iv) are not TFNs; however, these computational results can be approximated by TFNs. This study adopts a triangular fuzzy number, which is the most common membership function shape. [92].

Additionally, Geldermann et al. (2000) [41] defines the Function Implementation (f) as follows:

v. Function Implementation (f):

$$f\left(\widetilde{N}\right) = f((l_1, m_1, u_1)) = (f\,(l_1), f\,(m_1), f\,(u_1))$$

2.3.4. Literature Review on MCDM Methods and Fuzzy Logic

The information needed to assess the different decarbonisation scenarios especially in the context of energy transition is often unclear, uncertain and difficult to express with quantitative indicators [64]. As Phillis & Andriantiatsaholiniaina (2001) [93] have highlighted, sustainability is an inherently vague concept with parameters that are difficult to quantify.

Many methods of MCDM in fuzzy environment have been developed by Ölçer & Odabaşi (2005), Wang & Lin (2003) and Xu & Chen (2007) [94–96], and many applications benefited from these methods, such the applications of Chen & Tzeng (2011), Chen & Lee (2010); Chen et al. (2008); Chiou et al. (2005), Ding et al. (2005), Wang et al. (2008) [97–102].

Fuzzy AHP

Fuzzy analytical hierarchy process (AHP) has been applied in the energy sector in several studies. Heo et al. (2010) [103] utilized Fuzzy AHP to analyse the assessment factors for renewable energy dissemination program evaluation. Kahraman et al. (2010) [104] applied a comparative analysis for multi-attribute selection among renewable energy alternatives using fuzzy axiomatic design and Fuzzy AHP, while Kaya & Kahraman (2010) [105] used a Vlsekriterijumska Optimizacija I KOmpromisno Resenje (VIKOR) - AHP methodology under fuzziness to the selection of the best energy policy and production site. Luthra et al. (2015) [106] applied Fuzzy AHP for prioritizing of indicators to develop an integrated sustainability assessment framework for energy systems. Based on the results obtained, the 'Environmental' indicator dimension has been reported as the most important dimension for assessing the sustainability in energy planning and management. Fuzzy AHP has been also employed for the assessment of the effectiveness of national R&D actions relevant to renewable energy technologies [107,108], for the choice of goods suppliers [109–112], for the assessment of companies responsible for the collection and transport of hazardous waste [113], for the evaluation of hydrogen production technologies [114], for evaluating the complexity of project management [115]. Sagbas & Mazmanoglu (2014) [116] aimed to determine the weights of criteria for assessment of wind energy production alternatives located in Marmara region of Turkey. For this purpose, they developed a decision model based on the fuzzy AHP method. However, despite its wide and successful applications, in the extent analysis of fuzzy AHP, the priority weights of criterion or alternative can be equal to zero. In this situation, we do not take this criterion or alternative into consideration. This is one of the disadvantages of this method [117].

Fuzzy TOPSIS

The Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, similar to TOPSIS, also finds application in energy and environmental management and energy planning problems [118]. It has been used to evaluate the viability of renewable energy projects [119–122], to select the appropriate landfill site and method for managing municipal solid waste [123], for the selection of a suitable location for the installation of a power plant [124], for the selection of the most suitable alternative fuel in the transport sector [125], for the environmental assessment of energy suppliers [126], to choose the optimal supplier of goods [127]. Papapostolou et al. (2017) [24] presented a new extension of fuzzy TOPSIS method for prioritization of alternative energy policy scenarios to realize targets of renewable energy in 2030. In addition, the method can also be used on personnel selection problems [128]. Finally, systems based on fuzzy TOPSIS have also been applied for industrial control [129].

Fuzzy SAW

Simple additive weighting (SAW) has had applications in water management, business, and financial management. It is extremely simple to use, but users have applied it in limited applications [56]. The basic concept of SAW method is to find a weighted sum of rating the performance of each alternative on all attributes. A wide variety of Fuzzy SAW applications of solving real-world problems have been reported in the literature. Sagar et al. (2013) [130] present an approach of selection an appropriate maintenance strategy of material-handling equipment in the Punj Lloyd plant Gwalior (India) using Fuzzy SAW method. Rajaie et al. (2010) [131] dealt with the problem of choosing an appropriate contractor for a construction problem, which is a major concern in developing countries by developing a computation method based on Fuzzy SAW for the selecting the right contractor among those who participated in the tender process. Deni et al. (2013) [132] used the method with the aim to help and provide the best decision in the selection of high achieving students in the faculty level. To the best of our knowledge, Fuzzy SAW has a few publications in energy sector, while none of the have been applied in strategic energy planning.

Fuzzy PROMETHEE

The implementation of the PROMETHEE method with linguistic assessments instead of crisp values constitutes the fuzzy PROMETHEE method. This alteration of the original method has been successfully applied to many decision-making problems for ranking and selection among alternatives and fuzzy PROMETHEE has also been applied to studies in the field of energy policy, as it was shown in the introductory section.

In 2000, Goumas and Lygerou [39] proposes an extension of the PROMETHEE method for decision-making in fuzzy environment. In particular, the PROMETHEE II method has been extended to handle data in the form of fuzzy numbers [88]. Both methods, PROMETHEE II and Fuzzy-PROMETHEE, were then applied to the problem of ranking alternative scenarios for the exploitation of a geothermal field of low temperature fluids. Fuzzy-PROMETHEE resulted in a more realistic ranking where the imprecision of the data is taken into consideration. Cavallaro & Ciraolo (2013) [133] used fuzzy PROMETHEE method to make a comparison among a group of solar energy technologies. Chen & Pan (2015) [134] assessed low-carbon building measures. Five criteria and nine alternatives were identified within the context of high-rise commercial buildings in Hong Kong, which are centralized on technical, economic and environmental aspects of building performance. Geldermann et al. (2000) [41] proposed fuzzy PROMETHEE with trapezoidal fuzzy interval numbers and presented an application for the environmental assessment of iron and steel industries. Geldermann and Rentz (2001) [135] also presented fuzzy PROMETHEE for environmental assessment and developed a graphical sensitivity analysis.

In conclusion, with respect to the literature reviews mentioned above, to the best of our knowledge, this is the first fuzzy-PROMETHEE-based MCDM technique for group decision-making developed for ranking transformation pathways for achieving a sustainable European energy future. In doing so, the attempt is to extend the application domains of the fuzzy PROMETHEE method.

2.3.5. Implementation Steps of Fuzzy PROMETHEE

In the proposed methodological framework, the PROMETHEE method, introduced by Brans (1982) [50], is combined with fuzzy logic, developed by Zadeh (1965) [88], in order to exploit a method capable of tackling the transformation pathways problem. Additionally, group decision-making is embedded to depict the pluralism stemming from different stakeholders based on the Tavakkoli-Moghaddam et al. (2015) [136]. The steps of the extension of the fuzzy PROMETHEE method for group decision-making are explained in the following paragraphs [102].

Step 1: Determine alternatives (m), evaluation criteria (k) and group of decision-makers (n).

Step 2: Define linguistic variables and their corresponding triangular fuzzy numbers, based on which the evaluation of the criteria's importance and the ratings of the alternatives will take place.

In the current methodological approach, a five-scale linguistic variable fuzzy number was used, as in the research of Chen and Hwang (1992) [137]. Table 2 indicates the linguistic scales and corresponding triangular fuzzy numbers for weight of criteria and rating of alternatives, respectively. Figure 4 shows the membership function of triangular fuzzy numbers.

Table 2. Linguistic variables and fuzzy numbers.

Weights of Criteria	Fuzzy Number	Ratings of Alternatives
Very Low (VL)	(0.00, 0.00, 0.25)	Worst (W)
Low (L)	(0.00, 0.25, 0.50)	Poor (P)
Medium (M)	(0.25, 0.50, 0.75)	Fair (F)
High (H)	(0.50, 0.75, 1.00)	Good (G)
Very High (VH)	(0.75, 1.00, 1.00)	Best (B)

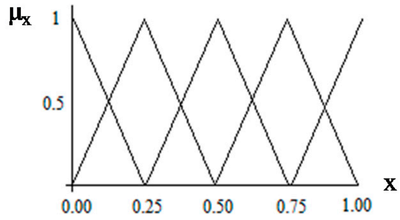

Figure 4. Membership function μ_x of triangular fuzzy numbers.

Step 3: Aggregate decision-maker evaluations. A decision is derived by aggregating the fuzzy weights of criteria and fuzzy rating of alternatives from n decision-makers. In addition, the preferences and opinions of n decision-makers with respect to j criterion (C_j) for the importance weight of each criterion and with respect to i alternative (A_i) for the rating of each alternative to each criterion can be calculated using the Equations (2) and (3).

$$\widetilde{w_j} = \frac{1}{n}\left[\sum_{e=1}^{n}\widetilde{w_j^e}\right] = \frac{1}{n}\left[\widetilde{w_j^1}(+)\,\widetilde{w_j^2}(+)\cdots(+)\widetilde{w_j^n}\right] \tag{2}$$

$$\widetilde{x_{ij}} = \frac{1}{n}\left[\sum_{e=1}^{n}\widetilde{x_{ij}^e}\right] = \frac{1}{n}\left[\widetilde{x_{ij}^1}(+)\,\widetilde{x_{ij}^2}(+)\cdots(+)\widetilde{x_{ij}^n}\right] \tag{3}$$

In the context of this study, it is also assumed that the opinions of the decision-makers are not equally important. In such case, the importance of decision-maker's i opinion is given by variable r_i and table R, as shown in equation (4), includes the importance weights of all decision-makers.

$$R = \begin{bmatrix} r_1 & r_2 & \ldots & r_n \end{bmatrix} \tag{4}$$

Therefore, Equations (2) and (3) are altered as follows:

$$\widetilde{w_j} = \left[\sum_{e=1}^{n} r_e\widetilde{w_j^e}\right] = \frac{1}{n}\left[r_1\widetilde{w_j^1}(+)r_2\widetilde{w_j^2}(+)\cdots(+)r_n\widetilde{w_j^n}\right] \tag{5}$$

$$\widetilde{x_{ij}} = \left[\sum_{e=1}^{n} r_e\widetilde{x_{ij}^e}\right] = \frac{1}{n}\left[r_1\widetilde{x_{ij}^1}(+)r_2\widetilde{x_{ij}^2}(+)\cdots(+)r_n\widetilde{x_{ij}^n}\right] \tag{6}$$

Step 4: Construct a fuzzy decision matrix and compute the aggregated fuzzy weight of criterion [37,92,136].

$$\widetilde{D} = \left[\widetilde{x_{ij}}\right]_{m\times k} = \begin{bmatrix} \widetilde{x}_{11} & \widetilde{x}_{12} & \cdots & \widetilde{x}_{1k} \\ \widetilde{x}_{21} & \widetilde{x}_{22} & \cdots & \widetilde{x}_{2k} \\ \vdots & \vdots & & \vdots \\ \widetilde{x}_{m1} & \widetilde{x}_{m2} & \cdots & \widetilde{x}_{mk} \end{bmatrix} \tag{7}$$

$$\widetilde{W} = \begin{bmatrix} \widetilde{w_1} & \widetilde{w_2} & \ldots & \widetilde{w_k} \end{bmatrix} \tag{8}$$

where $\widetilde{x_{ij}}$ is the rating of alternative A_i with respect to criterion C_j, and $\widetilde{w_j}$ is the importance weight of jth criterion.

Step 5: Choose the Type of the preference function P(d) and determine the corresponding thresholds. The use of Type V (Linear preference function with indifference area) is considered to be more suitable (Figure 5) [41]. The philosophy behind this selection is that fuzzy implementation aims at quantitating the qualitative criteria (as well as our original data, i.e., the evaluations of the alternatives). According to the literature [41], Type V is more appropriate for quantitative criteria. One reason for this is that the quantitative criteria receive constant values (unlike the qualitative that receive distinct e.g., bad, medium, good), so the preference function is preferable to be linear. For this reason, the remaining types of preference function (I, II, III, IV) are not selected in this study, as they cannot support the concept of linear preference, but instead define levels of preference, which is closer to the philosophy of the qualitative scale.

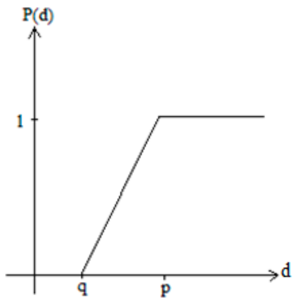

Figure 5. Type V preference function.

Initially, thresholds are defined as follows: indifference threshold q for criterion j is set to the smallest difference between two alternative ratings with respect to criterion j, and preference threshold p for criterion j is set to the maximum difference between two alternative ratings with respect to criterion j.

Step 6: Generate the fuzzy multi-criteria preference index $\widetilde{\pi}$ for each pair of alternatives A_i, A_j according to Equation (9) [41,92].

$$\widetilde{\pi}\left(A_i, A_j\right) = \frac{\sum_{t=1}^{k} \widetilde{w_t}\ (x)\ p_t(x_{it}(-)x_{jt})}{\sum_{t=1}^{k} \widetilde{w_t}} \tag{9}$$

where $p_t\left(x_{it}(-)x_{jt}\right)$ is the preference degree resulting from the comparison between alternatives A_i, A_j with respect to criterion t, which is calculated as the value of the preference function $p_t()$ based on the difference–subtraction operation (ii)–between the two alternative's ratings based on the Function Application operation (v). Finally, the total sum is calculated according to Addition operation (i).

Step 7: Calculate fuzzy Leaving Flow $\widetilde{\Phi^+}(A_i)$, as a measure of the superiority of the alternative A_i (10) and fuzzy Entering Flow $\widetilde{\Phi^-}(A_i)$, as a measure of the inferiority of alternative A_i (11). In the particular study we obtain a complete ranking of the four alternative transformation pathways. To this end, the difference of the aforementioned quantities produces the fuzzy Net Flow based on the PROMETHEE II method (12) [41,92].

$$\widetilde{\Phi^+}(A_i) = \frac{1}{m-1} \cdot \sum_{j=1}^{m} \widetilde{\pi}\left(A_i, A_j\right) \tag{10}$$

$$\widetilde{\Phi^-}(A_i) = \frac{1}{m-1} \cdot \sum_{j=1}^{m} \widetilde{\pi}\left(A_j, A_i\right) \tag{11}$$

$$\widetilde{\Phi}(A_i) = \widetilde{\Phi^+}(A_i)(-)\widetilde{\Phi^-}(A_i) \tag{12}$$

Step 8: The final total ranking is achieved after defuzzification of fuzzy Net Flow. There are many models that could be exploited at the defuzzification process but none of them could be considered as optimum under all circumstances. Based on the philosophy of outranking methods, and especially of PROMETHEE, the approach applied ought to be as easy as possible to be used at the decision-making process [41]. Consequently, the proposed assessment is based on the approach Centre of Area (COA) [138] according to equation (13), which is the most widely used option [139]. For the sake of brevity, we define $\widetilde{\Phi}(A_i) = x_i$.

$$x_i^{defuzz} = \frac{\int x_i \cdot \mu(x_i) dx_i}{\int \mu(x_i) dx_i} \tag{13}$$

where $\mu(x_i)$ is the membership function of fuzzy number x_i.

The final ranking of the problem's alternatives is obtained directly from sorting all the defuzzified x_i.

In order to implement and calculate the methodological steps suggested above the need for a new program that implements fuzzy PROMETHEE has occurred. Therefore, the algorithm explained in this section was implemented in Python 3.6 and the program was run in the Microsoft Azure Notebooks environment [140]. More precisely, the NumPy library was used for the numerical calculations and the csv library for the processing of spreadsheets that contained the input data, namely:

- Criteria Weights;
- Rating of the alternatives by the DMs;
- Parameters/Configurations for each scenario, which are the DMs' contributions and the threshold values.

3. Results

Following the presented steps, this research used a total of three decision-makers (DMs) Dr, r = {1, 2, 3}, four different criteria C_j, j = {1, 2, 3, 4}, and four alternative policy scenarios A_i, i = {1, 2, 3, 4}.

The next step concerns data collection so as to represent decision-makers' value system through definition of criteria weights and alternative ratings. Due to the diversity of stakeholders, three main decision-maker profiles were defined that represent: a policymaker(DM_1), an entrepreneur–representative of the energy industry (DM_2), and a researcher–representative of the academia (DM_3).

Their views regarding the importance of each criterion and the evaluation of the alternatives are shown in Tables 3 and 4. More particularly, Table 3 includes each DM's opinion on the importance of each criterion with regards to the transformation pathways assessment. The evaluation of the importance of each criterion are in the form of linguistic variables [Very Low (VL)-Low (L)-Medium (M)-High (H)-Very High (VH)] (see Table 2).

Respectively, Table 4 presents the performance of each of the four alternative pathways in each of the four criteria, according to the DMs' opinion [Worst (W)-Poor (P)-Fair (F)-Good (G)-Best (B)] (see Table 2).

Table 3. Criteria weights.

Decision-Makers	Weights			
	C_1	**C_2**	**C_3**	**C_4**
D_1	VH	M	VH	M
D_2	H	VH	M	M
D_3	M	M	VH	VH

At this point, it is important to underline that in an attempt to explore the stability of the produced results, sensitivity analysis was conducted. Sensitivity analysis helps to understand how the model variables react to input changes, and whether they are related to the data used to adapt the structure of the model, or to independent variables of the model [141]. This mechanism is used to increase the reliability and improve the outcomes of the model [142]. More precisely, multiple iterations (scenarios) of the methodology were carried out, that differentiate themselves in terms of DMs' importance and values of thresholds, as explained below.

Table 4. Rating of the alternatives by the DMs.

DM	Criteria	Alternatives			
		A_1	A_2	A_3	A_4
D_1	C_1	F	B	G	B
	C_2	P	F	G	B
	C_3	P	G	F	F
	C_4	G	G	P	F
D_2	C_1	F	B	G	G
	C_2	P	G	B	B
	C_3	F	G	F	G
	C_4	G	F	P	G
D_3	C_1	G	B	G	B
	C_2	P	G	G	B
	C_3	P	G	F	P
	C_4	B	F	P	F

Consequently, concerning the aggregation step (see Section 2.3.5, Step 3) of the above-mentioned views, four different scenarios were developed in an attempt to explore possible changes in the final ranking. These scenarios vary from each other in terms of importance that is attributed to each DM and therefore they produce different evaluation tables on step 4:

- 1st Scenario (reference): DMs are considered to be equal (33.33%) and their opinions contribute to the same extent in the final ranking.
- 2nd–4th Scenarios: In these scenarios, greater emphasis is placed on the opinion of one DM each time (60%), while the views of the other two contribute secondarily to the final ranking (20% each).

For each of the four scenarios and based on the preference function selected in step 5, the values of the preference threshold p and indifference threshold q were initially selected so as not to affect the results, as explained in step 5. Because of this, the first scenarios are labelled as "no threshold" when commenting on the results.

Based on these four scenarios, four additional repeats of the method were produced in order to assess the sensitivity of the final ranking, by progressively decreasing the value of preference threshold p and increasing the value of indifference threshold q, as suggested by the literature (Table 5). It should be highlighted that as part of the sensitivity analysis of the results, other iterations of the method were carried out with intermediate threshold values. However, these were not considered necessary to be presented, as the rankings for the different threshold values in Table 5, are sufficient to confirm that the results are sufficiently robust.

During the final steps, the fuzzy PROMETHEE algorithm written in Python generates the fuzzy multi-criteria preference index $\widetilde{\pi}$ (step 6), the flows (step 7) and at last implements the defuzzification process (step 8) that produces the overall ranking of the transition pathways.

More precisely, leaving, entering and net flows of each alternative for all eight scenarios are presented on Tables 6 and 7. As mentioned in step 7, the fuzzy Leaving Flow $\widetilde{\Phi^+}(A_i)$ measures the sum of preference that alternative A_i is better from another options and fuzzy Entering Flow $\widetilde{\Phi^-}(A_i)$ demonstrates the sum of preference that other options are superior to alternative A_i, while the final ranking of the four alternative transformation pathways is obtained from the difference of the aforementioned quantities, which produces the fuzzy Net Flow based on PROMETHEE II method.

Table 5. Values attributed to thresholds.

Iterations	**Criteria**	**Thresholds**	
		p	**q**
No thresholds	C_1	1.00	0.25
	C_2	1.00	0.00
	C_3	1.00	0.00
	C_4	1.00	0.00
With thresholds	C_1	0.65	0.60
	C_2	0.65	0.35
	C_3	0.65	0.35
	C_4	0.65	0.35

Repetitions for the first, second and fourth scenarios produced similar results and a graph is illustrated to depict schematically the corresponding flows, indicatively for the first scenario (Figure 6). Respectively, for repetitions of the third scenario (where the opinion of the representative of the energy industry has priority) the flows are presented in Figure 7. The same results are obtained in the case of "with threshold".

Table 6. Alternative flows for all scenarios (no thresholds).

Scenario 1 equal DMs–R = [0.33, 0.33, 0.33]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	1.14	2.42	1.61	2.22
Entering	3.11	1.12	1.94	1.22
Net	−1.97	1.3	−0.33	1
Scenario 2 priority on D_1–R = [0.6, 0.2, 0.2]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	1.04	2.49	1.56	2.22
Entering	3.14	1.04	1.94	1.2
Net	−2.1	1.46	−0.38	1.02
Scenario 3 priority on D_2–R = [0.2, 0.6, 0.2]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	1.02	2.35	1.67	2.34
Entering	3.29	1.13	1.86	1.1
Net	−2.26	1.22	−0.19	1.23
Scenario 4 priority on D_3–R = [0.2, 0.2, 0.6]				
Flows	Alternatives			
	A_1	A_2	A_3	A_4
Leaving	1.38	2.42	1.64	2.11
Entering	2.9	1.19	2.05	1.41
Net	−1.52	1.23	−0.41	0.7

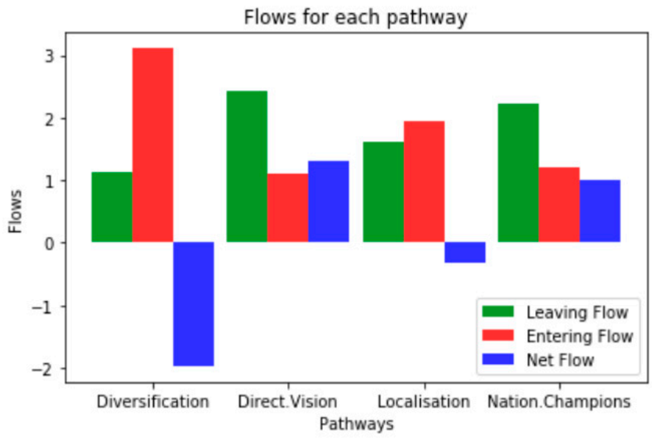

Figure 6. Flows representation for alternative pathways in scenario 1 (no thresholds).

Table 7. Alternative flows for all scenarios (with thresholds).

Flows	Alternatives			
	A_1	A_2	A_3	A_4
Scenario 1 equal DMs–R = [0.33, 0.33, 0.33]				
Leaving	1.01	2.13	1.49	1.99
Entering	3.2	0.94	1.53	0.95
Net	−2.19	1.19	−0.03	1.04
Scenario 2 priority on D_1–R = [0.6, 0.2, 0.2]				
Leaving	0.89	2.25	1.46	1.95
Entering	3.18	0.82	1.53	1.01
Net	−2.29	1.43	−0.07	0.94
Scenario 3 priority on D_2–R = [0.2, 0.6, 0.2]				
Leaving	0.93	2.07	1.46	2.01
Entering	3.39	0.86	1.45	0.77
Net	−2.46	1.22	0.01	1.23
Scenario 4 priority on D_3–R = [0.2, 0.2, 0.6]				
Leaving	1.21	2.15	1.53	1.94
Entering	3.08	1	1.63	1.12
Net	22121.87	1.15	−0.09	0.82

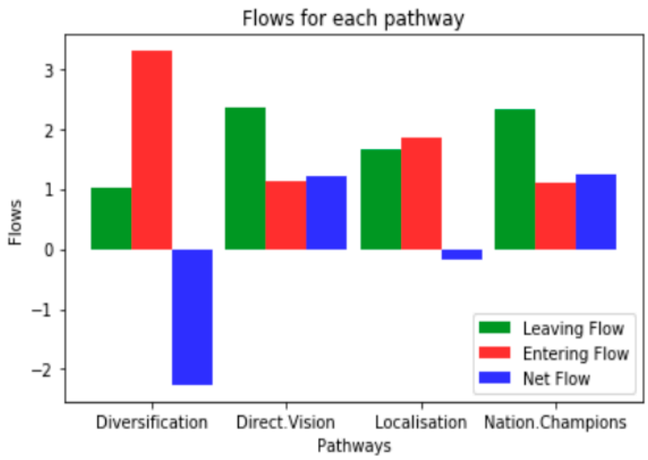

Figure 7. Flows representation for alternative pathways in scenario 3 (no thresholds).

The resulting ranking is $A_2 > A_4 > A_3 > A_1$ for all scenarios, with the only exception taking place in the 3rd scenario where A_2 is marginally supplanted by A_4, as presented in Table 8.

Table 8. Summary of rankings for all scenarios.

Alternatives	Scenarios							
	No Threshold				With Threshold			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
A_1	4	4	4	4	4	4	4	4
A_2	1	1	2	1	1	1	2	1
A_3	3	3	3	3	3	3	3	3
A_4	2	2	1	2	2	2	1	2

4. Discussion

First of all, the comparative study of the above results demonstrates a high rate of agreement between the rankings of different scenarios, confirming the practical interest and usefulness of the proposed methodology as a tool to support the decision-making process of assessing the energy transformation pathways. Also, according to a relevant study by Cavallaro & Ciraolo (2013) [133] that compared a set of solar energy technologies using fuzzy PROMETHEE, the method seems to be able to provide a technical–scientific decision-making tool that can be efficiently integrated with linguistic information giving valuable assistance to decision and policymakers in the field of energy.

In the majority of all scenarios, "Directed Vision" stands out as the most preferred pathway, followed by "National Champions". These two pathways show positive net flow values, which is translated as follows: The measure of the superiority of these pathways (Leaving flow) is greater than the absolute value of the measure of their weakness (Entering flow). However, this does not hold true for the other two alternatives, namely "Localisation" and "Diversification", which have negative net flows.

The only cases where "National Champions" supplants "Directed Vision" are the two iterations of the third scenario. Although this supremacy is only marginal, since net flows of the two pathways differ only to the second decimal, it is worth exploring, why this has occurred. More specifically, the differentiation element between scenarios is found in the greater weight that is attributed to a different decision-maker each time. In turn, each decision-maker differs from the others in terms of alternative ratings and criteria weights.

In this case, the third scenario concerns the second decision-maker (DM_2) and by studying Tables 2 and 3, the following are observed: For none of the criteria, DM_2 underestimates "Directed Vision" compared to the other decision-makers, whereas DM_2 gives a higher ranking to "National

Champions" only in regard to the criterion C_4. However, the fourth criterion does not have the greatest importance for DM_2 and therefore this differentiation is not the main reason why changes are observed in final rankings. Instead, the predominant cause of the small variations in rankings lies in the attribution of weights, since DM_2 gives greater importance to C_2, in comparison with the other decision-makers, a criterion to which "National Champions" performs better than the "Directed Vision". In other words, "National Champions" has a noticeable sensitivity to C_2, as a change in its weight is likely to cause deviations of the results.

This assessment is dedicated to introducing and providing a direction towards a most preferable pathway concept, as well as an overall approach that should be taken into account by a future model-based analysis of the necessary transformation of our energy sector to cope with the requirements of a decarbonisation.

Policymakers and all relevant stakeholders could be facilitated in the drawing the energy transition priorities take into account the results of the assessment. "Directed vision" pathway lays emphasis on cooperation between countries on technology advancement, diversification of flexibility options for RES integration (but with prioritising of centralised solutions), a strong expansion in grid capacity and a balanced mix in energy supply, including new nuclear, CCS, and RES (with focus on centralised options). Remarkably, it is noted here the strongest EU energy systems integration (prioritizing interconnections). Towards this direction, the cross-border cooperation seems to play a crucial role in achieving the energy transition. Finally, this analysis may serve as a guidance to policymakers towards their efforts to plan climate and energy strategies by using the information of this approach and prioritizing uncertainties from an environmental and energy perspective.

5. Conclusions

This paper presents a multi-criteria approach based on an extended fuzzy PROMETHEE for group decision-making. The approach is used to evaluate alternative transformation pathways for achieving a free-carbon and sustainable energy future in the EU.

The recognition of the multidimensional nature inherent in the alternative choices regarding the European energy future and the treatment of the problem as a multifactorial one abolishes the obsolete one-dimensional approach that seeks to find a transformation pathway that will be optimal in light of a specific objective, such as the participation of RES in the energy mix or the transition cost.

The proposed approach and the developed methodological framework could be a useful tool for decision-makers and stakeholders in the energy market. First, by choosing a representative set of criteria, the realistic modelling of the problem under study is achieved, since the fundamental and often conflicting aspects that determine whether strategies followed will lead to a sustainable energy system, are clearly outlined. Secondly, with the definition of thresholds, criteria weights and alternatives ratings, an accurate mathematical representation of the decision-makers' preference system is achieved, thus integrating them into the process of the pathways evaluation.

Of course, the impact of the linguistic variables is remarkable, too. The process becomes friendlier to the decision-makers and at the same time the uncertainty in their words is taken into consideration and it is encoded in the input data thanks to the use of fuzzy numbers. Moreover, the proposed methodology contributes to achieving consensus as it enables the views of different decision-makers to be aggregated, thus promoting group decision-making, which is inherent in the application problem, given that numerous and heterogeneous stakeholders are involved and that they have different views and intentions.

Taking into account the overall results of this methodological process, it appears that the decision-makers unanimously believe that "Directed Vision" and "National Champions" have the best prospects of thriving and bearing positive consequences concerning EU's attempt to transform the energy sector and achieve its decarbonisation. According to the majority of scenarios, the more progressive "Directed Vision" outperforms the more conservative "National Champions". However, the generalization of the aforementioned finding is considered precarious and it is more realistic to suggest that there are more to be gained if policymakers and those involved in the energy market formulate proposals and strategies that divert the European energy future from "Localisation" and "Diversification" pathways.

To further improve the decision model, it is suggested to assess it under more realistic conditions. Including more experts and policy-makers in the process will result in even more efficient modelling of the problem and hence more realistic results will be extracted that correspond to the specific value system of each decision-maker. The reason for this is that decision-makers, not only attribute different weights to the criteria, but they can also suggest new criteria to include, so that their personal opinions are reflected. Consequently, an enriched and more complete set of criteria will be formed. More precisely, when assessing the pathways financial and societal impact could be taken into consideration, as well. Additionally, further evaluation of the same alternatives could be pursued, too. In other words, it is proposed that the pathways be evaluated and compared based on their performance in key technological aspects (e.g., case studies on renewable energy sources, smart grids, energy efficiency, sustainable transportation, carbon capture and storage technologies and nuclear safety). The development of this alternative model is meant to shed light on the more complex and specialized technological factors that play a major role in the energy systems.

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