Multi-Criteria Applications in Renewable Energy Analysis, a Literature Review

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Abstract Energy impacts so many aspects of our lives. This makes it necessary to evaluate multiple aspects when we are evaluating energy alternatives. This chapter introduces us to a spectrum of tools for this evaluation.

1 Introduction

Energy is a necessity for human beings, but current energy resources are forecast to be limited in the coming years with apparent destructive consequence to the environment. Renewable energy is emerging as a solution for a sustainable, environmentally friendly and long term, cost-effective source of energy for the future. Renewable energy alternatives are capable of replacing conventional sources of energy in most of their applications at competitive long term prices [1, 2]. Selecting the appropriate source of energy in which to invested is a task that involves different factors and policies. Renewable energy decision-making can be viewed as a multiple criteria decision-making problem with correlating criteria and alternatives. This task should take into consideration several conflicting aspects because of the increasing complexity of the social, technological, environmental, and economic factors [3]. Traditional single criteria decision-making approaches cannot handle the complexity of current systems and this problem [4]. Multi-criteria methods provide a flexible tool that is able to handle and bring together a wide range of variables appraised in different ways and thus offer useful assistance to the decision maker in mapping out the problem. As this work demonstrates,

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multi-criteria analysis can provide a technical-scientific decision-making support tool that is able to justify its choices clearly and consistently, especially in the renewable energy sector [5].

2 Overview of Multi-Criteria Decision-Making Methods

Multi-criteria decision making (MCDM) is a branch of operation research models and a well known field of decision-making. These methods can handle both quantitative as well as qualitative criteria and analyze conflict in criteria and decision makers [6]. Several classification and categorization exist but in general these methods can be divided into two categories: multi-objective decision-making (MODM) and multi-attribute decision-making (MADM) [7]. In MODM, the decision problem is characterized by the existence of multiple and competitive objectives that should be optimized against a set of feasible and available constraints [8] rather than, as in MADM, the evaluation of a set of alternatives against a set of criteria. MADM is one of the most popular MCDM methods to be adopted to solve problems associated with different perspectives [9]. They contain several different methods of which the most important are Analytic hierarchy process (AHP), Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE), ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing REality or more commonly—ELECTRE), and Multi-attribute utility theory (MAUT) [4]. The comparison of MCDM methods related to renewable energy planning is discussed in the literature [6, 10–14]. In a previous analysis by Pohekar et al., multi-attribute utility theory (MAUT) was the most common MCDM method used in energy planning literature, AHP, PROMETHEE, ELECTRE, MAUT, fuzzy methods and decision support systems (DSS) [6].

The main objective of MADM is to select the alternative that has the highest score according to the set of the evaluation criteria. A descriptive summary of the most commonly used multi-criteria decision-making methods is presented below:

- Analytic Hierarchy Process (AHP): A MADM method was first introduced by Saaty [15]. In AHP, the problem is constructed as a hierarchy breaking down the decision top to bottom. The goal is at the top level, criteria and sub-criteria are in middle levels, and the alternatives are at the bottom layer of the hierarchy. Input of experts and decision makers is considered as pair-wise comparison and the best alternative can be selected according to the highest rank between alternatives.
- Analytic Network Process (ANP) : The ANP methodology is a general form of the AHP, both were introduced by Saaty [16, 17]. Although AHP is easy to use and apply, its unidirectional relationship characteristic cannot handle the complexity of many problems. ANP, however, deals with the problem as a network of complex relationships between alternatives and criteria where all the elements can be connected. Cheng and Li an empirical example to illustrate use of ANP [18].

- Preference ranking organization method for enrichment evaluation (PROMETHEE): This method is characterized by ease of use and decreased complexity. It uses the outranking principle to rank the alternatives and performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteria. Up to now, the family of PROMETHEE have included PROMETHEE I & II [19].
- The elimination and choice translating reality (ELECTRE): This method is capable of handling discrete criteria of both quantitative and qualitative in nature and provides complete ordering of the alternatives. The analysis is focused on the dominance relations between alternatives. It is based on the outranking relations hips and exploitation notions of concordance. The outranking method uses pair-wise comparison between alternatives [13]. The family of ELECTRE includes ELECTRE I, II, III, IV.
- The technique for order preference by similarity to ideal solutions (TOPSIS): The basic concept of this method is that the selected alternative is the one that has the best value for all criteria, i.e. has the shortest distance from the negative ideal solution [20].
- Multi-attribute utility theory (MAUT): This is one of the most popular MSDM methods. The theory takes into consideration the decision maker's preferences in the form of the utility function which is defined over a set of attributes, where the utility of each attribute or criterion doesn't have to be linear [9].

In general, MCDM methods have four basic steps that support making the most efficient, rational decisions: (1) Structure the decision process, alternative selection and criteria formulation (2) Display tradeoff among criteria and determine criteria weights (3) Apply value judgment concerning acceptable tradeoffs and evaluation, and (4) Calculate final aggregation and make decision [6]. There are many discussions in the literature about which MCDM methodology is best to use, and controversy about which is the "right" method applied to a real life problem. Multi-criteria analysis is used to select the "best fitted" solution from multi-attribute distinct options [21].

3 Multi-Criteria Decision Analysis in Renewable Energy

Adopting and choosing alternative energy sources is a multidimensional decision making process that involves a number of different characteristics at different levels: economic, technical, social, and environmental [22]. From this point of view, multi-criteria analysis appears to be a suitable tool to merge and analyze all perspectives concerned with the decision making process, by establishing a relationship between all alternatives and factors that influence the decision. It can provide a technical-scientific decision-making support tool that is able to justify its choices clearly and consistently in the renewable energy sector [23]. It is important

Table 1 Literature Review on MCDM Methods and Application to Renewable Energy Issues

Application area	AHP/ ANP	ELECTRE	PROMETHEE	Fuzzy sets	Others[a]	Sum
Renewable energy planning and policy	[24–30][b]	[31, 32]	[33, 34]	[31, 35–37]	[3, 4, 12, 38–42]	23
Renewable energy evaluation	[43–47]	[48, 49]	[19, 50]	[49, 51, 52]	[47, 53–58]	19
Project selection	[1, 18, 59–62]	[23, 63]	[5, 63–65]	[60, 66–68]	[69–73]	24
Environmental	[74, 75]	[76]	[76]		[14, 21, 77–81]	11
Sum	20	7	9	11	26	

[a] Others include: VIKOR, TOPSIS, SWA, SIMUS, UTADIS, value trees
[b] Numbers in brackets refer to reference number

to realize that since there will be conflicting view points and different hypothetical solutions, the "best" choice resulting from applying MCDM methods would be the best negotiated solution, and not explicitly the optimum.

This chapter presents a review of selected literature to analyze and underline the application area and expansion of the most used MCDM methods in renewable energy analysis. Classification of the year, application area, and method used is presented to highlight the trends of research in alternative energy decision-making. After researching the literature, the application area of MCDM in renewable energy was divided into four categories: renewable energy planning and policy, renewable energy evaluation and assessment, technology and project selection, and environmental (Table 1). Renewable energy planning and policy refers to the assessment of a feasible energy plan and/or the diffusion of different renewable energy option. The key factors are: adoption to reach a certain national target, decision factors, national planning, and system indicators. Renewable energy evaluation refers to the assessment of different alternative energies or energy technologies. Choosing between alternatives could be for assessing the "best" energy to be utilized in electrical or thermal energy, or any other systems. Project selection and allocation refers to site selection, technology selection, and decision support in renewable energy harnessing projects. Environmental is concerned with the literature discussing alternative technologies from an environmental perspective and climate issues.

3.1 Renewable Energy Planning and Policy

Selecting between alternative energy sources has usually focused only on cost minimization. It is widely recognized now that energy planning is a much more complicated decision with many actors and factors involved. Pohekar and

Ramachandran presented a review and analysis of several published papers on MCDM and highlighted their applications in the renewable energy area [6]. Wang et al. performed a literature review on MCDM methods used for the selection of energy and its applications to energy issues. The review shows that there are four main criteria categories for the evaluation of energy source and site selection problems: technical, economic, environmental, and social [13].

Georgopoulou et al. utilized MCDM-namely ELECTRE III- to reach a compromise in regional energy problems by analyzing the results and actors' reaction [32]. Beccali et al. developed a case study to illustrate the use of the ELECTRE method and a fuzzy set theory. Both methodologies were applied to the development of a renewable energy diffusion strategic plan. The case study explored advantages and drawbacks of each methodology [31]. Diakoulaki et al. used MCDM to examine the relative contribution of different factors and characteristics in reaching the desired level of energy efficiency and how they can be further exploited in energy policy making [39]. Afgan and Carvalho defined energy system elements and indicators which are used in the analysis and assessment of the relationship between an energy system and its environment. The authors considered five indicators and presented the effect of the priority rating and given weight of each criteria on each selected energy system alternative [3]. Kowalski attempted to combine participatory multi-criteria analysis (PMCA) with scenario building for analyzing energy policy making combined with public and stakeholder inputs [33].

Keeney et al. presented another application of MCDM methods in national energy policy. The authors followed a systematic approach of value trees to come up with a set of criteria that would be used in the assessment of alternative energy systems in Germany [41]. Lee et al. Analyzed the competitiveness of Korea among 30 other nations in hydrogen energy technology development using the analytic hierarchy process (AHP) and two potential scenarios to determine criteria [28]. Lee et al. used AHP and DEA to prioritize energy efficiency technologies in the sector of long-term national energy planning [82].

The main objective of using MCDM is to be able to make more rational and efficient choices to ensure that public values are reflected in decisions. Hobbs and Horn used different MCDM methods to develop a set of recommendations in energy planning and policy through an interview process and several group discussions between stakeholders. The authors discussed the difference between using MCDM for evaluation of criteria and alternatives instead of monetizing all criteria, and concluded that the best approach is a combination of the two methods [12]. Enzensberger et al. emphasized the importance of engaging all stakeholder groups in the criteria evaluation process and explained how considering different view points can help policy planners to anticipate possible problems at an early stage [40].

Renewable energy is foreseen as a sustainable, economically sound alternative to conventional energy resources and can be utilized in many different ways. Köne and Büke in keeping with the sustainability perspective, presented a multi-criteria analysis (ANP) to determine the best alternative technology for electricity generation in Turkey [26]. Zhao et al. utilized an AHP model to evaluate alternative power supply technologies and determine the best option according to the criteria of sustainable development including environmental cost and energy security. The study would help the government of Guangdong Providence to plan for the best power generation technology when expanding the local installed capacity [75]. Topcu and Ulengin dealt with the problem of selecting the most suitable electricity generation alternative for Turkey. They focused on a multi-attribute decision-making evaluation of energy resources and provided an integrated decision aid framework for the selection of the most suitable multi-attribute method for ranking alternatives [34]. Önüt et al. employed analytic network process (ANP) to evaluate the most suitable energy resources for the manufacturing industry in Turkey [29]. Afgan et al. used multi-criteria evaluation in the assessment of different options of conventional hydrogen energy systems and compared them with renewable energy systems [38]. Hamalainen and Karjalainen utilized AHP and value trees to determine the relative weights of the evaluation criteria of Finland's energy policies [24]. Kablan used AHP framework to support management in the prioritization process of energy conservation policy instruments in Jordan [25]. San Cristóbal applied the VIKOR method to the assessment of several renewable energy alternatives in order to select the most fit project for helping the Spanish government to reach the target of 12 % total renewable energy in 2010 [4].

3.2 Renewable Energy Evaluation and Assessment

To ensure a sustainable future, the assessment of new energy sources should include all the pillars of sustainability, environmental, economic, and social attributes [83]. Afgan and Carvalho used the sustainability assessment method for the evaluation of quality of selected hybrid energy systems by using analysis of the system composed of different technologies and other selected indicators, such as economic, social, and environmental, as measures of the criteria [53]. Afgan et al. evaluated potential natural gas usage in the energy sector and classified the criteria of the analysis as economic, environmental, social, and technological [54]. Burton and Hubacek investigated a local case study of different scales of renewable energy provision for local government in the UK and compared the perceived social, economic, and environmental cost of small-scale energy technologies to larger-scale alternatives [55]. Chatzimouratidis and Pilavachi assessed different power plant types and compared between traditional and new RE power generating technologies according to the technological, economic and sustainability characteristics. They presented sensitivity analyses by comparing the original criteria weights with four alternative scenarios, changing each criteria weight at each scenario [43, 44]. Roth et al. evaluated the sustainability of current and future power supply technologies in Switzerland and compared available options [58].

When trying to select any alternative energy, conflicts among criteria and stakeholders should be taken into consideration. Haralambopoulos and Polatidis presented a new group decision-making framework of multi-criteria analysis for ranking renewable energy projects. The suggested framework utilized the PROMETHEE II outranking method to achieve group consensus in evaluating renewable energy projects. The proposed framework was applied to data from different scenarios in a case study of exploitation of geothermal energy sources in the island of Chios, Greece [50]. Polatidis and Haralambopoulos presented a new decision-making framework of participatory multi-criteria approach where stakeholders can be engaged in the planning and decision process. The methodology was applied to a number of case studies in Greece in order to evaluate renewable energy options for future investments [57].

Considering the different scenarios for adopting renewable energies would give more insight about the feasibility of such adoption and the conflict in policies or alternatives. Beccali et al. utilized ELECTRE-III to assess an action plan for the selection and diffusion of renewable energy technologies at the regional scale in the island of Sardinia under different scenarios [48]. Cavallaro and Ciraolo applied a multi-criteria method in order to support the selection and evaluation of one or more of the solutions and make a preliminary assessment for the feasibility of installing wind energy turbines in a site on the island of Salina in Italy [56]. Daim et al. utilized MCDA to evaluate the feasibility of two clean power generation technologies, wind and clean burning coal, in the Pacific Northwest [84].

Many researchers applied two or more MCDM methodologies to assess the feasibility of technologies by comparing the results and investigating shortcoming of each alternative. Kahraman et al. utilized two different multi-criteria decision making approaches to select the most appropriate renewable energy in Turkey. Fuzzy axiomatic design (AD) and fuzzy Analytic hierarchy process where applied to the same set of criteria and alternatives and the results from both methodologies were compared [52]. Nigim et al. applied two different MCDM tools to the same set of data for ranking alternative energy of a community in southern Ontario, Canada. The first tool was AHP and the other was Sequential Interactive Model for Urban Sustainability (SIMUS) [45]. Oberschmidt et al. introduced PROMETHEE MCDM method as an applicable approach to comparing alternatives for electricity and heat supply based on a case study of the bio-energy village in Germany [19]. Pilavachi et al. applied AHP methodology to evaluate nine options of electrical generating technologies that use natural gas or hydrogen as fuel [46]. Tzeng et al. compared two methodologies, VIKOR and TOPSIS, to determine the best compromise solution among alternative fuel for buses in Taiwan's urban areas where AHP was applied to determine the relative weights of evaluation criteria [47].

3.3 Project Selection and Allocation

One of the main issues recently is adopting renewable energy to ensure a sufficient electricity supply. Expansion of current projects or planning new ones to meet energy demands is a task that involves finding a set of resources and ranking them in an optimal manner. MCDM process can provide a systematic approach to rank alternatives and select the most "suitable" technology. Aragonés-Beltrán et al. applied two multi-criteria decision analysis methods: a hierarchy AHP model and a network-based ANP model, and compared the resulting data to select between different photovoltaic (PV) solar technologies proposed to be invested in a power plant [59]. Begic and Afgan evaluated the options of energy power systems for Bosnia Herzegovina under a multi-criteria sustainability assessment framework in order to investigate options for the selection of new capacity building of this complex system [69]. Cavallaro applied an outranking methodology of MCDA to evaluate different PV technologies according to given criteria for selected in the process of thin film production [5], extended a classic TOPSIS MCDA methodology to the framework of fuzzy-set theory, and used it to compare different heat transfer fluids used in CSP to examine the feasibility of using a new molten salt alternative [67]. The Kaya or Istanbul study, another example, used multi-criteria decision-making analysis to determine the most appropriate RE in Istanbul and the most suitable area to establish it in [60].

Project selection and allocation requires a complex decision-making process that involves a search of the available opportunities and an evaluation of the options by different stakeholders of multiple aspects, both qualitative and quantitative. Aras et al. determined the most convenient location for a wind observation station to be built using analytic hierarchy process (AHP) [1]. Cherni et al. investigated the outcome of applying a new multi-criteria decision support system methodology (SUREDSS) to the case of a rural area in Colombia in calculating the most appropriate energy option for providing power and fulfilling local demand [70]. Goletsis et al. studied energy planning processes to rank the projects and developed a multi-criteria ranking method, a hybrid of ELECTRE-III and PROMETHEE methods. They combined an integrated project ranking methodology for groups with multi-criteria methods in an integrated methodology such as the prioritization of project proposals in the energy sector of Armenia [63]. Project prioritization by Goumas and Lygerou and Goumas et al., extended a multi-criteria method of ranking alternative projects, PROMETHEE, to deal with fuzzy input data. The proposed method was applied for the evaluation and ranking of geothermal energy exploitation projects [64, 72].

Ivanova et al. assessed the feasibility of wind power plant expansion in an electric power system using a hierarchical multi-criteria approach [73]. Lee introduced wind farms and developed the criteria for successful implementation in China, taking into account experts' opinions and stakeholders, input. Lee AHI et al proposed a new multi-criteria decision-making model based on AHP and associated with benefits, opportunities, costs, and risks, to select a suitable wind farm project [61].

3.4 Environmental

Different multi-criteria methods have been applied to assess renewable energies from an environmental perspective [44, 75]. MCDM has been increasingly adopted in the area of environmental planning due to the growing awareness of these issues. Zhou et al. provided a survey and literature review and an update of the survey on decision analysis in energy and environmental modeling by Huang [77]. The update showed that the importance of multiple criteria decision-making methods and energy-related environmental studies has almost tripled since 1995 [14, 85]. Greening and Bernow (2004) referred to the potential of MCDM in energy and environmental policy planning [21]. Lahdelma et al. discussed these methods for environmental planning and management [78]. Patlitzianas et al. presented an integrated multi-criteria decision-making approach for assessing the environment of renewable energy producers in the fourteen different member states of the European Union accession [81]. Chatzimouratidis and Pilavachi evaluated different power plants and compared between traditional and new RE power generating technologies according to their sustainability, level and kind of emissions they release using, and impact on the living standard using AHP [43, 44, 74, 86]. Mirasgedis and Diakoulaki compared the external costs of power plants that used different energy sources with a multi-criteria analysis where environmental impacts were expressed in a qualitative scale. They identified similarities and disparities in the obtained rankings and clarified on the basis of the fundamental principles of the two approaches, external cost estimates and multi-criteria analysis [80].

3.5 Fuzzy Sets

In many decision-making situations, it is relatively difficult to obtain exact numerical values for the criteria or attributes [51, 87]. Thus, many parameters cannot be evaluated accurately and the data of different subjective criteria and their weights are usually expressed in linguistic terms by the decision maker [36]. In order to overcome this uncertainty in human judgment, fuzzy logic can be applied which deals with vague information by applying membership functions. Fuzzy set theory is integrated to overcome the ambiguity in the preferences. In the literature, different studies had used fuzzy analysis in energy planning and energy policy [31, 35–37, 49, 52, 60, 66–68].

Kahraman and Kaya proposed a fuzzy multi-criteria decision-making methodology which can evaluate linguistic terms, fuzzy numbers, and precise numerical values. The proposed methodology was applied to the case of Turkey to determine the energy policy in the country, by sorting the best available alternatives [36]. Mohanty et al. demonstrated the application of fuzzy set in project selection. The study illustrated an application of fuzzy ANP along with fuzzy cost analysis in selecting R&D projects [68].

3.6 Comparison between MCDM Methods

As shown before, multi-criteria decision-making analysis has been applied to solve many real world problems. Many researchers recently have been interested in comparing two or more MSDM methodologies and analyzing the advantages or drawbacks of each method. Some researchers applied several methods to real life problem data and compared the results obtained from those methods. Theodorou investigated three different MCDM methodologies, namely: AHP, ELECTRE, and PROMETHEE, and their application on energy planning for different subsidy schemes [88]. Chu et al. provided a comparative analysis of Simple Additive Weighting (SAW), TOPSIS and VIKOR, which demonstrated the similarities and differences of these methodologies in achieving group decisions [11]. Hobbs and Meirer compared the methods with respect to simplicity of applications and feasible expected outcomes [89]. Opricovic and Tzeng conducted a comparative analysis of VIKOR and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods using a numerical example to explain their similarities and differences. The authors extended the comparison of VIKOR method with TOPSIS to other MCDM approaches, namely, Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE) and ELimination and Choice Expressing REality (ELECTRE), by using a numerical example and compared results of analysis [90, 91].

4 Conclusion

In general, evaluating energy systems is a complex analysis that can be defined as a multi-dimensional space of different indicators and objectives. The use of multi-criteria decision analysis (MCDA) techniques provides a reliable methodology to rank alternative renewable energy resources, technologies and projects in the presence of different objectives and limitations. Even with the large number of available MCDA methods, none of them is considered the best for all kinds of decision-making situations. Different methods often produce different results even when applied to the same problem using same data. There is no better or worse method but only a technique that fits better in a certain situation. The current research does not give a clear view about the trend in literature, but can give an insight about the direction it is going. It is noticed that AHP is the most used methodology of all MCDM methods. This can be credited to its simple structure and the ability of an analyst to negotiate results until consistency is achieved, offering near consensus on judgment. The main question that remains is how to choose the appropriate MCDA methodology in alternative energy decision-making.

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