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Applications of Multi-Criteria Decision-Making (MCDM) Methods in Renewable Energy Development: A Review

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Abstract
Renewable energies are noticeably developing due to their various advantages such as low greenhouse gases emission, availability, and reducing cost trend. In order to achieve the favorable objectives in energy projects, it is crucial to consider all the related parameters affecting the decision-making. The Multi-Criteria Decision-Making (MCDM) methods are reliable and efficient tools for policy-making and achieving the most appropriate solution. These approaches consider the influential factors and their relative importance in prioritizing the alternatives. Since the outcome of the MCDM approaches depends on the employed algorithm and the criteria used, this article focuses on the studies related to the applications of these methods in renewable energy technology selection. The aim of the present work is to extract the criteria that are necessary to be used in decision-making for renewable energy systems. In addition, the approaches employed for improving the performance of MCDM methods as decision-making aids are represented. According to this review study, the technical, economic, and environmental criteria are utilized in the majority of decision-making research works. Moreover, some of the studies have considered other criteria such as social and risk to achieve more reliable decisions. Some ideas are represented in the reviewed research works such as integrating different methods and using fuzzy sets instead of crisp sets to improve the performance of the MCDM methods and reduce the uncertainties.

Keywords: *MCDM, Renewable Energy, AHP, Sustainable Development.*

1. Introduction

The types of energy systems and their key features such as efficiency, cost, and reliability play a key role in energy-related policy-makings. The environmental issues faced by greenhouse gas production necessitate the development of energy technologies with a lower emission compared with the conventional fossil fuel-based systems [1–3]. As an example, according to the findings of a research work [4], using solar PV panels with a 5000 MW capacity in Iran can result in up to 9.025 Mt reduction in carbon dioxide emission compared with using the conventional fossil fuel plants used in this country. Renewable energy sources are applicable for various purposes including desalination, water heating, and power generation [5–8]. Different types of renewable energy technologies such as wind turbines, solar PV panels, and geothermal facilities are applied for energy demand [9, 10]. The appropriateness of the renewable-based energy type for each case depends on different factors such as the geographical and weather condition, social acceptance, required capacity, and the current energy system [2, 11]. In these cases, employing MCDM is an acceptable method to demonstrate the most favorable type of technology.

Multi-Attribute Decision-Making (MADM) or Multi-Criteria Decision-Making (MCDM) methods are applied in different fields of science [12–14]. These approaches are utilized for making preference when there are different alternatives defined based on various attributes, which are conflicting in the majority of the cases [15, 16]. The decision-making, selection of the final alternative, is carried out based on the attribute achievement. In order to find the most favorable alternative, inter- and intra-attribute comparisons are required [12]. Different studies, which focus on the decision- and policy-makings, use MCDM methods to evaluate the possible alternatives and prioritize them [17].

In the field of energy engineering, these methods are employed for various purposes including technology or location selection [18–21]. For instance, Nazari *et al.* [22] used TOPSIS as an MCMD approach to find the most proper location for PV-based power plant in Iran. In a study [23], this method was employed to figure out the most appropriate material to be used in solar cells.

Since the reliability of MCDM approaches for policy-makers is very crucial, it is important to find the factors influencing it. The factors applied for evaluation of alternatives are among the most important parameters affecting the performance of MCDM methods. Considering all the criteria affecting the decision-making is necessary to produce a deeper insight into the appropriateness of the alternatives and their rankings. Moreover, the utilized approach can influence the final decision and its reliability. Due to the necessity of the mentioned factors, a comprehensive literature review is required to evaluate them.

In this work, an in-depth review was carried out on the research works applied to MCMD methods in the field of renewable energy. The included studies in the present article for review have focused on the technology or type of renewable energy sources. Finally, according to the methods and results of the reviewed references, their main findings and outcomes are summarized.

2. Multi-Criteria Decision-Making Approaches in Renewable Energy Systems

Selection of the most proper renewable-based energy system depends on several factors [24, 25]. These factors should be considered in the process of decision-making to achieve the most favorable outcome. Doukas *et al.* [26] applied MCDM method in order to formulate the technological energy priorities. The criteria used in their study were divided into four main parts including economic, environmental, technological, and social. Each main criterion has some branches, as shown in Figure 1. In their study, 10 alternatives were considered for evaluation, as represented in Figure 2.

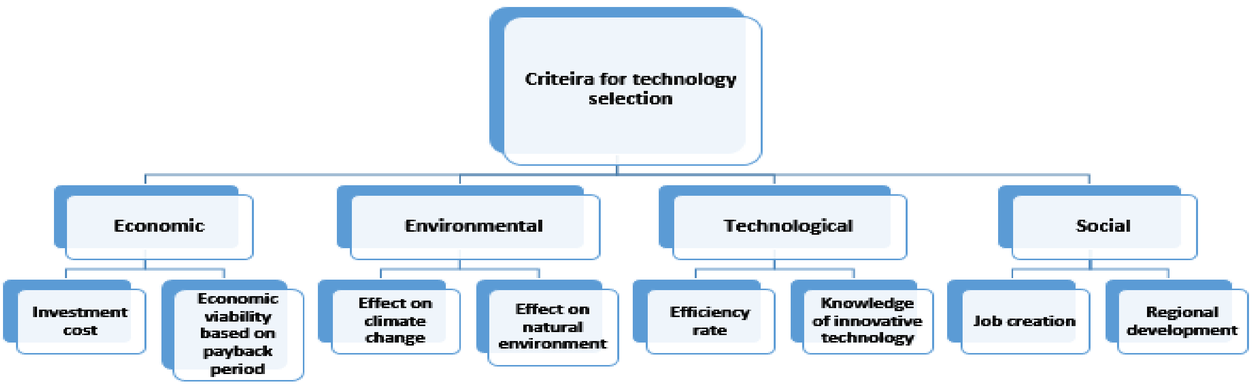

Figure 1. Considered criteria for formulating the priorities of sustainable energy technologies [26].

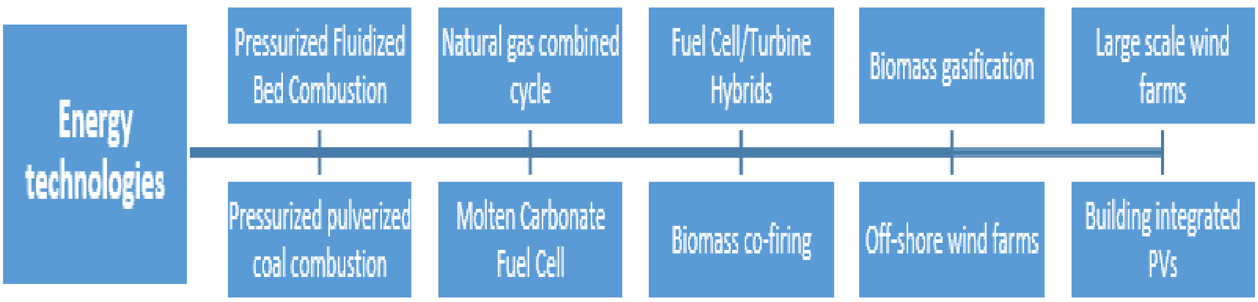

Figure 2. Evaluated alternatives as energy technologies [26].

The importance of the considered criteria for decision-making significantly affects the results and the priority of the alternatives. In a research work conducted by Chamzini *et al.* [27], different MCDM approaches were employed to distinguish the most appropriate renewable energy technology. Similar to the previous study, the criteria were divided into some sub-criteria as investment ratio, power (since the technologies with different capacities were considered in the study), useful life, operating hour, period of implementation, operation and maintenance cost, and carbon dioxide emission per year. Among these criteria, the highest importance belonged to power that was followed by carbon dioxide emission and useful life.

The MCDM approaches can be integrated with other methods to assess the alternatives for a specific purpose. In a research work conducted by Çelikbilek *et al.* [28], integrated grey-based MCDM was employed in order to prioritize the renewable energy sources. In this study, grey DEMATEL was applied to obtain the relations between the assessment criteria; moreover, the assessment criteria weights were determined by employing grey ANP. Finally, the considered alternatives including solar, wind, geothermal, hydroelectric, and biomass energies were ranked by applying grey VIKOR. The criteria used in this study covered different aspects including risk, economic, and technical, as represented in Figure 3.

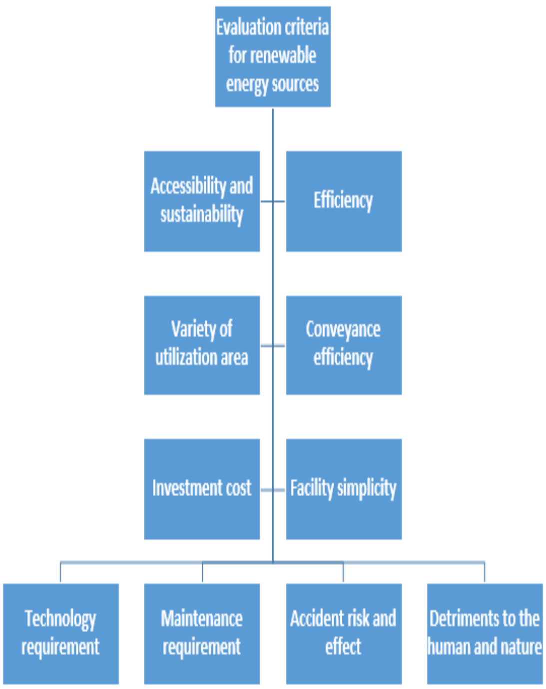

Figure 3. Evaluation criteria for renewable energy sources [28].

In the cases that information is vogue and incomplete, fuzzy sets are an appropriate solution to overcome uncertainty [29]. Due to this fact, the fuzzy MCDM approaches are efficient tools for ranking the alternatives for policy-makers [30–32]. In a research work, Zhang *et al.* [33] utilized an enhanced MCMD approach on the basis of integral and fuzzy measure in order to rank the clean energy sources for Jaingsu, China. The factors considered in their study were Technology Readiness Level (TRL), and safety, as technical criteria, investment cost and feed-in tariff, as economic criteria, emission of carbon dioxide and land utilization, as environmental criteria, and job creation as social criteria. Kahraman *et al.* [29] applied AHP under fuzziness for energy technology selection in Turkey. In addition to the criteria used in the previously mentioned studies, socio-political criteria were considered in their study. The alternatives considered for evaluation in their research work were oil, wind, nuclear, geothermal, hydropower, solar, biomass, natural gas, coal, and lignite. The criteria used in the study and their sub-criteria are shown in Figure 4. In another similar study [34], these criteria were used to rank just renewable-based energy sources including solar, geothermal, wind, wood and waste, and hydro-power. In order to evaluate the effect of the applied approach, Axiomatic Design (AD) and AHP were used. In the AHP method, the alternatives are assessed based on the pairwise comparison and flexible assessment of experts, while in the AD method, the most appropriate alternative is selected on the basis of maximum satisfying functional requirement. The results obtained revealed that using both methods led to similar outcomes. In addition to the applicability of the fuzzy MCDM approach for selection of renewable energy type, it is useful for prioritizing types of a specific renewable energy technology. Cascales *et al.* [35] applied the fuzzy TOPSIS method to rank the PV cells. The criteria used in their study for determining the most proper type of PV cell were cost of manufacturing, pay-back time of energy, greenhouse gas emission in the process of manufacturing, market share, and energy conversion efficiency.

In order to overcome the problems faced due to using a single approach, MCMD methods are modified. In a study done by Beltrán *et al.* [36], AHP/ANP was employed to prioritize investment projects of solar-thermal power plants. AHP approach was used due to its ease of use; however, since it was not efficient in handling the complexities of the some real word problems, ANP was applied as a modified form of AHP.

Comparison of the results obtained revealed that utilizing ANP led to a more favorable reflection of the problem complexity. It should be mentioned that the process of decision-making was classified into three levels. First of all, the projects were assessed in order to find if they were profitable to be analyzed or not. Afterwards, the projects were evaluated to find if they were appropriate for spending further resources for analysis or not. Finally, the remaining projects were evaluated to be prioritized. The main criteria considered in the 1st stage of their study were divided into three groups including risks, costs, and opportunities. Each one of the mentioned criteria has some sub-criteria, as represented in Figure 5. Some other criteria such as technology availability, ease of access, and delays in grid connection were considered in levels 2 and 3.

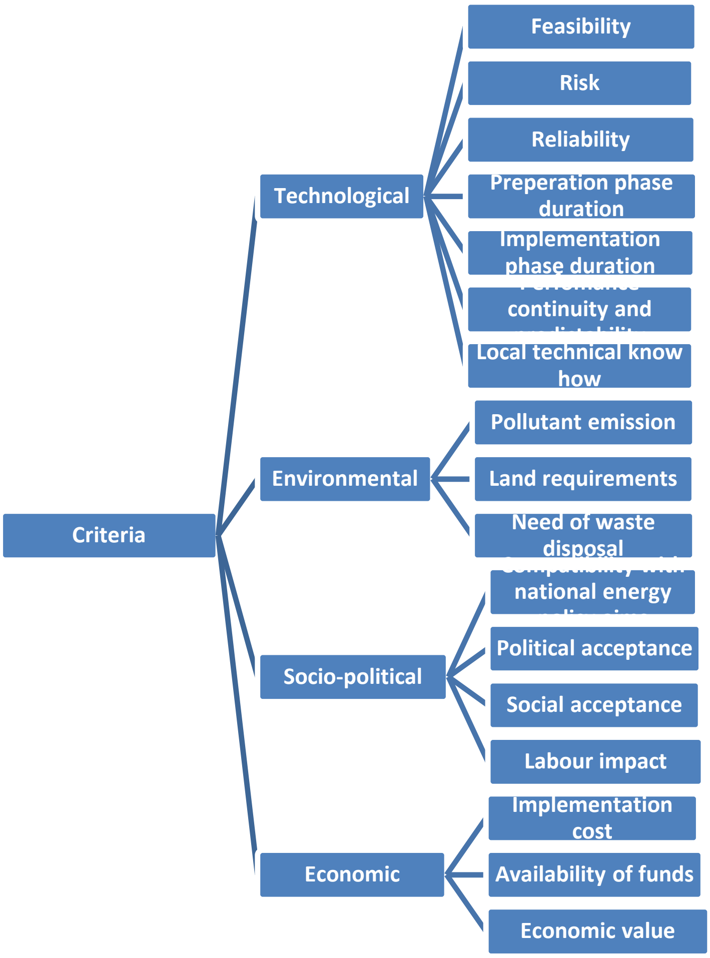

Figure 4. Criteria and sub-criteria used for energy system selection in Turkey [29].

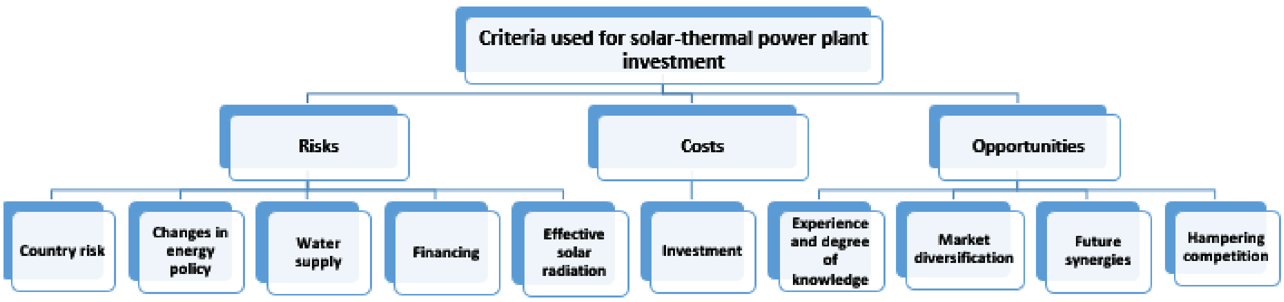

Figure 5. Criteria used in the 1st level of evaluation of the solar-thermal power plant [36].

Integrating different MCDM methods has been suggested by some researcher for planning renewable energy systems [37]. In these types of approaches, a method is applied for determining the weights of the criteria and the other one is employed for prioritizing the alternatives based on the obtained weights. For instance, in a study carried out by Kaya *et al.* [38], the fuzzy VIKOR-AHP method was employed in order to prioritize renewable energy alternatives in Istanbul, Turkey. In their study, pairwise comparison matrix was considered as a proper approach for determining the criteria weights based on the AHP method. Subsequently, the VIKOR method was utilized for ranking the alternatives of renewable energy systems, which were hydraulic, solar, geothermal, wind, and biomass. The criteria used in this research work covered different aspects including economic, technical, and social, as shown in Figure 6. In addition to selecting the most favorable type of renewable energy, which was wind, for the case study, site selection was performed for the wind farm.

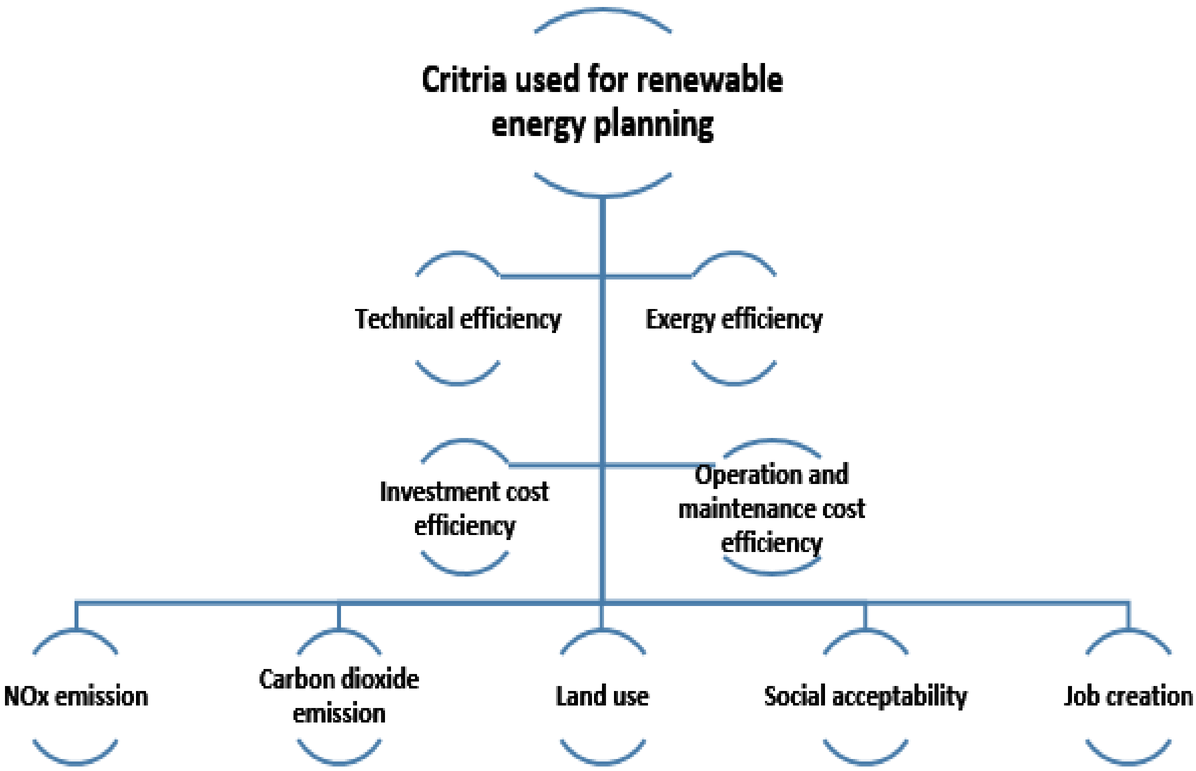

Figure 6. Utilized criteria for renewable energy selection in Istanbul, Turkey [38].

In order to summarize the results of reviewed sources, it can be concluded that economic and environmental criteria are considered in all renewable energy technologies. The economic factors have noticeable impacts on the implementation of the projects and the affordable cost of generated power by the applied technology. Furthermore, due to the concerns about environmental issues [39, 40], it is crucial to consider greenhouse gas emission of the systems used for power generation. Technical features of the technologies are considered in the technology selection of renewable energy systems. These features affect in different ways such as cost of generated power, size, and emission of NOx and carbon dioxide [4, 41, 42]. In addition to the indicated criteria, some other factors such as risk and social acceptance must be included as the criteria for technology selection [43, 44]. The technologies with lower risk of failure are more favorable. Moreover, since social acceptance is required for success of each project [22, 45], consideration of this factor leads to a more reliable output.

3. Recommendations for future research works

Several studies have been reviewed in the previous section of the article. According to the literature review, MCDM approaches are widely used in different aspects of renewable energies such as site selection and technology prioritizing. Most of the reviewed studies, which have focused on the applications of MCDM in technology selection, are used for prioritization of the renewable energy type. Future research works can use these methods for ranking the type of technology applicable to a specific renewable energy technology. For instance, this method can be employed to find the most appropriate type of wind turbine or the heat exchangers used in geothermal facilities. Moreover, according to the investigations represented in the reviewed articles, the applicability of the MCDM methods can be broadened by utilizing fuzzy set. Due to this fact, by applying fuzzy sets, it is possible to solve more complex decision-making problems related to the renewable energy technologies. Integrating different MCDM methods is another suggestion for future studies to improve their effectiveness and applications. Different suggestions for improving the performance of the MCDM approaches are represented in Figure 7.

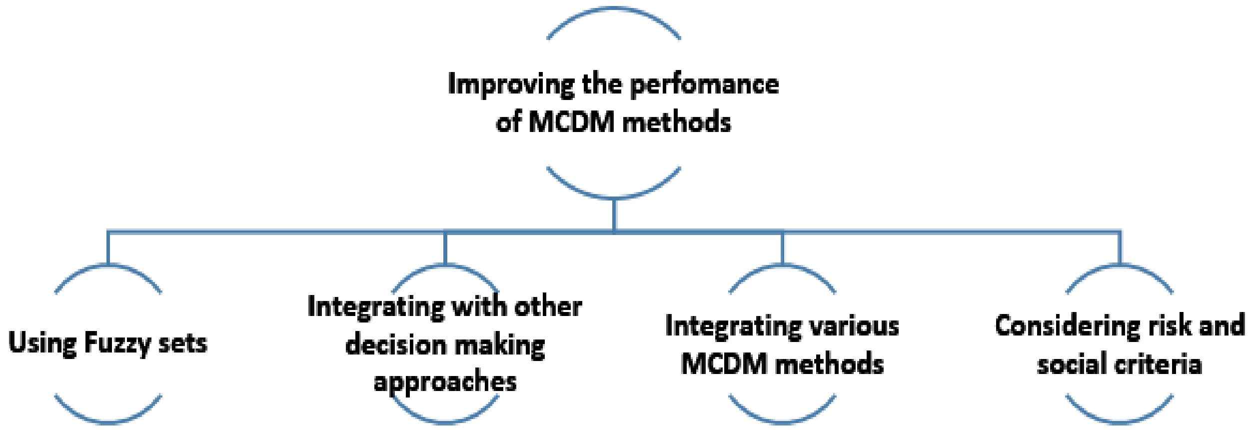

Figure 7. Suggestions for improving the performance of MCDM methods.

4. Conclusion

Due to the wide applications of MCDM methods in energy policy-making, it is necessary to gain an insight into the parameters that must be considered to reach a reliable outcome. In this regard, the studies conducted on the applications of MCDM approaches for renewable energy technology selection are reviewed and their most important findings are represented. According to the reviewed research work, the following points can be concluded:

- In renewable technology selection, economic, environmental, and technical features play a key role.
- In addition to the above-mentioned criteria, some other criteria such as risk and social acceptance are considered as the factors for alternatives evaluation.
- Integrating different MCDM approaches instead of using a single type for both criteria weighting and alternatives prioritization can result in a more reliable outcome.
- In addition to integrating MCDM approaches with each other, they can be coupled with other decision-making aids to reach a more favorable performance.
- By utilizing fuzzy sets instead of crisp sets, it is possible to overcome some problems such as uncertainty.
- In addition to applicability of MCDM approaches in selecting renewable energy type, they can be used for evaluating the specific technologies used as a renewable energy system, i.e. type of solar cell.

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