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Bohra, Shabbir Saleh ; Anvari-Moghaddam, Amjad

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A comprehensive review on applications of multicriteria decision-making methods in power and energy systems

Shabbir S. Bohra[1] | **Amjad Anvari-Moghaddam**[2]

[1]Department of Electrical Engineering, Sarvajanik College of Engineering & Technology, Surat, India

[2]Department of Energy Technology, Aalborg University, Aalborg, Denmark

Correspondence
Shabbir S. Bohra, Department of Electrical Engineering, Sarvajanik College of Engineering & Technology, Surat-395001, India.
Email: bohra.shabbir@gmail.com

Summary

Energy has been considered as one of the essential needs of mankind along with air, water, and food and witnessed evolution of civilization since evidence of human life. Managing energy resources is one of the challenging problems being capital intensive. Addressing this involves critical thinking and decision making with all possible aspects, technically known as set of primary and secondary criteria. There exist a number of literature sources addressing applications of multicriteria decision-making (MCDM) in different energy-related areas. Some are focusing on energy policy making, few are explaining site selection of solar PV, wind farm, and hydro power plants, and a few are describing applications in load management. Moreover, a few literature in this field elaborates various MCDM methods and their applications. In this article, an extensive and exhaustive study is carried out incorporating almost all possible applications of MCDM in renewable energy area. Various energy-intensive applications are mapped with MCDM methods along with governing sensitive parameters. Hence, this study facilitates practicing engineers, decision-makers, academician, and researchers to identify areas and MCDM techniques researched over the past decade in energy sector for planning, managing, selecting renewable resources, etc.

KEYWORDS

analytic hierarchy process, decision-makers, energy planning, energy storage system, multicriteria decision-making, renewable energy

1 | INTRODUCTION

According to recently published data, around 15% of world population accounting approximately more than 1 billion people do not have privilege to use electrical energy, which is considered as one of the highest grade energies and a strong backbone for civilization development. Out of this number, around 237 million belong to India and 635 million are living in African countries. Majority of this population belong to rural areas while being deprived of modern energy sources.[1] Encouragingly, the electrification rate has accelerated since 2015, with 153 million additional people being provided access to electricity each year.

The world is targeting aggressively to meet sustainable development goals (SDG),[2] but it is expected not to fully meet the goals by 2030 with present pace of progress. The SDG Target 7.1 is to ensure common access to sustainable, reliable, affordable, and modern energy services by 2030, Target 7.2 is to improve significantly the contribution of renewable energy in the world-wide energy blend, and Target 7.3 is to double the global rate of enhancement of energy efficiency. It is clear that the aforementioned SDG-7[3] targets could only be fulfilled by meticulous planning and developing a sustainable and reliable electrical energy infrastructure involving more renewable energy resources. The developed nations want to become more sustainable while maintaining or enhancing the economy and developing ones aim to become developed to compete with other countries causing ever increasing energy demands for future. In spite of intermittent in nature, solar energy– and wind energy–based generation lead the favorite renewable energy sources (RESs) offering various merits such as sustainability, pollution free after deployment, considerable life span, and technological advancement.[4] In addition to these, hydro, ocean, geothermal, biomass, and recently hydrogen-based generation units are also added to the list of preferred energy sources.

Globally, the world had seen a great rise in electrification growth during 2015-2017. In 2017, 20 nations with the maximum access deficit, which is measured in terms of the percentage of population lacking access to electricity, comprising around 78% of the worldwide population. Thus, efforts to provide electricity to these countries will decide in significant percentage of improvement completed on SDG indicator 7.1.1. Myanmar, Kenya, and Bangladesh have made the remarkable growth after 2010, at an annual rate of over 3% of these 20 countries. Though, since 2010, the electrification rate has been observed to be 0.80% per year, the as average annual achievement, lagging behind the expected rate, needed to attain universal access of electricity by 2030. In order to compensate this gap, this rate needs an improvement to 0.86% annually from 2018 to 2030.[5,6] Due to many challenges faced by countries having limited or no access, the projection has been revised to the access rate to 92% by 2030, leaving 759 million people around the world deprived from electricity. The report of electricity tariff, the 2018 edition of the World Bank's Regulatory Indicators for Sustainable Energy (RISE) illustrates that fundamental, subsistence-level consumption of electricity (30 kW-hours [kWh]/month) is unreasonable (costing around more than 5% of monthly household income) for the 40% underprivileged households in almost 50% of the access-limited countries, which represents around 285 million population.

There are a number of countries which are generating a substantial amount of the energy from renewable sources. The leading countries are (a) Iceland, which is listed the top in generation through renewable energy sources and producing surplus electricity per individual than any other country in the world. Nearly, 100% of their energy needs are contributed from renewable energy sources (hydropower and geothermal generation are major ones) due to its exceptional landscape; (b) Norway caters around 98% of its energy-needs from renewable sources and hydropower has been one of the main sources of the production followed by wind and thermal energy; (c) Kenya's renewable energy share is roughly 70% of its total need and targeting to achieve 100% by green energy by 2020; (d) Uruguay, in the last decade managed to considerably diminish its carbon emission without accounting government subsidies and maintaining its consumer costs; (e) Sweden has also invested massive in installing wind power, solar power, energy storage, smart grids, and green transport system; (f) Germany currently caters more electricity needs through its renewable sources than its coal and nuclear generation together; and (g) China is among the most aggressive investors in area of renewable energy–based generation. It caters around 25% of their total energy demand from renewable sources along with very large chunk of energy from nonrenewable sources and (h) the UK, wind power is the main source for renewable energy production. The share of energy from wind farms is more than from coal. (i) The renewable energy share in Denmark is 30% of all energy demand. Denmark produces almost twice as much wind energy per capita among other industrialized countries in the Organization for Economic Co-operation and Development (OECD)[7]; 47% of total energy demand was met by wind based generation in 2019.[8] In addition, more than 30% of renewable energy comes from bio-energy, and the country is aiming to become fossil fuel-free by 2030.[9] (j) In the United states, just 17% of nation's energy comes from renewable sources; hydro, wind, and solar contributing 7%, 7%, and 2%, respectively, in 2019.[10]

Nevertheless, RESs have been gaining popularity nowadays due their sparkling features like, sustainability, low carbon footprint, and modularity. However, most of them suffer from intermittent power generation capability. Furthermore, the cost of units (in $/kWh) also makes the integration of RESs into existing power system more challenging. Unlike centralized gigantic power producers, RES-based units are smaller and hence need large number of scattered deployment based on available potential or power density to cater demand. This further introduces complexity into planning of RES-based generation and optimization in terms of selecting the best technologies and sizing, efficiency, reliability, and cost-effectiveness aspects along with compulsion to lower cost of energy (CoE) to an attractive and acceptable level. In such scenario, the revenue generation aspects would be emphasized more and other apparently intangible perspectives, like technological maturity, social acceptance, environmental friendliness, etc. are overlooked.

Decision-making is a very crucial aspect at different stages for success of any project, from its planning to operational phases and final execution. The projects dealing especially with electrical energy generation, transmission, and utilization in variety of applications include multiple aspects of extended life period and requires huge amount of investment and also has significance influence on deciding growth rate of any country. There are number of decision making techniques used by planners, managers, and operators, such as Marginal Analysis, Financial Analysis, Break-Even Analysis, Ratio Analysis, Operations Research Techniques, Game Theory, Decision Tree, etc. The multicriteria decision-making (MCDM) term was suggested by Zeleny[11] and is one of the proven methodologies of operational research, which takes into account multiple factors in order to generate ranking of set of alternatives.[12] In Reference 13, a number of MCDM methods have been studied and compared for their applicability to different subject areas with a detailed discussion of benefits and drawbacks. In order to address significant aspects of decision-making, an attempt has been made in this review to provide readers with a better opportunity about existing MCDM methods together with their field of applications.

The various MCDM techniques have already been applied extensively and effectively to address large-scale socio-technical decision issues pertaining to ranging from planning of energy policy to selecting a portfolio of renewable energy technologies for sustainable energy systems.[14] Due to vast range of applications, several review articles are available on MCDM applications in renewable energy technologies and systems.[15,16] A few reviews on MCDM explain the techniques of multiattribute decision-making (MADM), participation and role of stakeholders, and quantification of related criteria. Such study work helps researchers to identify an effective and reliable method of MCDM[17] in any of the areas of energy sector.

For last few decades, the planning of electrical energy has changed dramatically from single objective system to more complex systems addressing multiple and mutually conflicting criteria.[18] Historically, decision-making for simple and small-scale energy systems involves either maximizing profit or minimizing expenditure incurred in order to offer lower CoE. However modern energy system has to be planned with number of interleaved criteria and most of the time they are mutually contradicting, for example, energy-efficient solutions never expected to be less expensive, reliability is achieved at higher costs, simple and inexpensive systems may emit higher environment pollutants or hazardous gases, and so on. So, this makes selection of components more difficult with a wider perspective of sustainability. Thus, an expert decision-making system is required, which addresses necessary economic, social, and environmental, political factors while overcoming ever-increasing demand of energy keeping sustainable development utmost important. In order to solve such complex problems, MCDM is evidenced to be one of the preferred techniques for efficient energy planning. The history of MCDM has been explained in References 19,20.

The key objective of this study to provide a detailed and wide perspective of existing MCDM methods related to applications in diversified energy sectors. The task is appreciated through exhaustive literature review on MCDM related to its applications in energy storage system (ESS), power systems policy-making (PSPM), load management/demand side management (DSM) in domestic, commercial or institutional premises and utilities, site selection of large-sized wind farms, solar PV farms and hydro power plants, and placement of electrical conditioning equipment along transmission lines. The most of the literature discusses an issue of site selection of either solar PV or wind farm, project selection, sizing of components, selection of batteries, etc. Unlike them, this review discusses various energy-intensive applications and suggested MCDM methods by researchers across the globe. And hence, it helps planners or managers of specific application to identify suitable MCDM method with relevant parameters and weights computed for given scenario and accordingly one can estimate for his case.

This review will help readers to get a deeper insight into the MCDM methods and their applications from planning to operation management of power and energy systems. It also outlines the typical stages of each popular MCDM method and complemented by the scores assigned by experts' and common or global weights, which lead to the final conclusion of problem. More importantly, this study aims to facilitate practicing engineers, decision makers, stakeholders, permitting agencies, engineers involved in permitting process, academician and researchers to identify areas and MCDM techniques researched over the past decade in energy sector for planning, managing, and selecting renewable resources.

This article is organized as follows: Section 2 discusses an overview of methods available in power systems, such as planning or placement of energy sources. Section 3 provides details about applications of MCDM techniques in various energy applications; the salient feature of methods in energy domain is mentioned in Section 4, and it is followed by the conclusions in Section 5.

2 | OVERVIEW OF MCDM METHODS

In order to deal with MCDM issues, the principal requirement is to identify number of attributes or criteria associated with the problem and methodology adopted to address the issues (ie, identification of problems). Subsequently, suitable data or information have to be gathered through which the choices of decision-makers (DMs) can precisely be employed into and considered (ie, prioritizing). Then subsequently listing a group of feasible options or approaches will be achieved ensuring the objective (ie, assessing options). After completing these procedures, the subsequent part is selection of an appropriate technique that makes evaluation and outranking of the feasible options or strategies easier (ie, identifying solutions).[21] Alinezhad and Khalili[22] explained the significance of experts' role in evaluation of any project by DMs. The decision-making task requires the precise expression of objectives, deciding possible different solutions, evaluating their feasibility, assessing the impacts and the results of implementing each solution, and finally, selecting and implementation of the solution. They defined MCDM as amalgamation of decision-making techniques and elaborated on 27 various techniques like Simple Multi-Attribute Rating Technique (SMART), Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHE-I-II-III), VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR), QUALItative FLEXible (QUALIFLEX), Superiority and Inferiority Ranking (SIR), Multi-Objective Optimization Ratio Analysis (MOORA), COmplex PRoportional ASsessment (COPRAS), DEcision-MAking Trial and Evaluation Laboratory (DEMATEL), Analytic Network Process (ANP), Multi-Attribute Utility Theory (MAUT) and ELimination Et Choice Translating Reality (EELCTRE I-II-III), etc.[22] Energy systems planning assessment for optimum investment for Saudi Arabia has been done by Taylan et al.[23] The hybrid MCDM methods such as fuzzy analytic hierarchy process (FAHP), fuzzy VIKOR, and TOPSIS (Technique for Order Preferences by Similarity to Idle Solution) are more found more effective in evaluating set of energy schemes for investment considering eight potential options against nine tangible criteria. The key criteria for site selection renewable energy sources like solar onshore and offshore wind, wave and tidal are reviewed by Shao et al.[24] Moreover, the significant site selection steps, (a) criteria selection, (b) data normalization, (c) criteria weighting, (d) alternative assessment, and (e) result validation are explained. The classification of major criteria for technology selection for renewable energy–based generation is illustrated by Kamari et al.[25] Furthermore, an example of solar-thermal power plant and significant secondary criteria for risk, cost, and opportunities is also elaborated, and possible improvements such as integration of multiple MCDM methods and involvement of fuzzy sets in MCDM methods are also highlighted.

The MADM is a process of collecting attributes to be assessed in order to find the best suitable option among all considered alternatives. It makes use of mainly two major approaches for analyzing attributes: (a) compensatory model, which permits trade-offs between chosen attributes, uses scoring, compromising, and concordance technique and (b) a noncompensatory model which is relatively simple and applied to limited applications; it uses maxmin, maximax, dominance, conjunctive constraint, and lexicographic methods.[26] Ilbahara et al has discussed factors playing a pivotal role in selecting AHP, ANP, TOPSIS, ELECTRE, and PROMETHEE techniques in renewable energy planning area.[27] The merits and drawbacks of various MCDM methods, like SAW, WPM, AHP, TOPSIS, VIKOR, ELECTRE III, and SHARE MCA, are discussed for existing small run-of-the-river hydropower plant in Italy for optimal flow release and SHARE MCA, WPM, and VIKOR are found to be the most feasible ones for such applications by Vassoney et al.[28]

The MADM task is the methodology to determine the best suitable alternative among several, contradictory, and collaborative criteria.[29] Various methods such as the weighted sum and the weighted product methods, based on multiple attribute utility theory (MAUT), have been developed to manage MCDM problems. In order to evaluate alternatives, a function known as utility function is created by aggregating all selected criteria into a specific single dimension according to MAUT technique. Therefore, the primary purpose of MAUT is to discover sensible aggregation operator, which represents the choices of the DM. Kaya and Kahraman[30] investigated the MAUT for the renewable energy alternatives assessment.

Moreover, a further classification can be done from the perspective of DMs' inclination since their opinions vary in terms of perception, subjectivity, and expertise. An authority might not express his/her preferences at all or might show preferences by attributes or alternatives. In addition to that, based on the collected information, the attributes are categorized in subjective and objective, in the form of a range or with definite numbers. These set of attributes necessitate the use of a suitable MADM method to evaluate the objective. Generally, decision-making in the area of economics, science, and operations research (OR) requires a normative analysis and prescriptive analysis.[21]

Typically, a decision-making process comprises seven stages for any project planning regardless to its applications as illustrated in Figure 1. To achieve the goal and objective, selecting the most suitable decision-making method, which fits the nature of the problem, should be the initial step toward success. The MCDM method can be summarized in five main steps[32]) and shown in Figure 2:

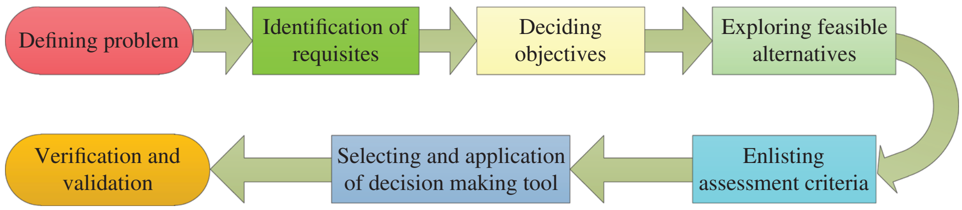

FIGURE 1 Typical decision-making process for project planning[31]

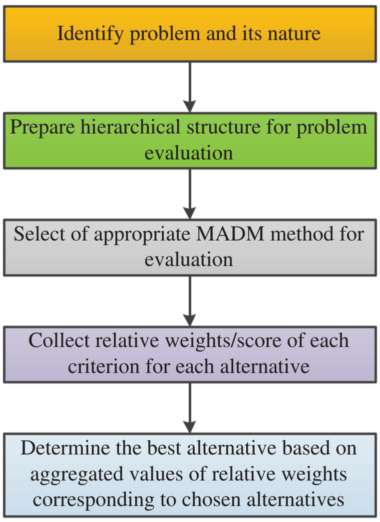

FIGURE 2 The flowchart for typical MCDM method for evaluation of a project

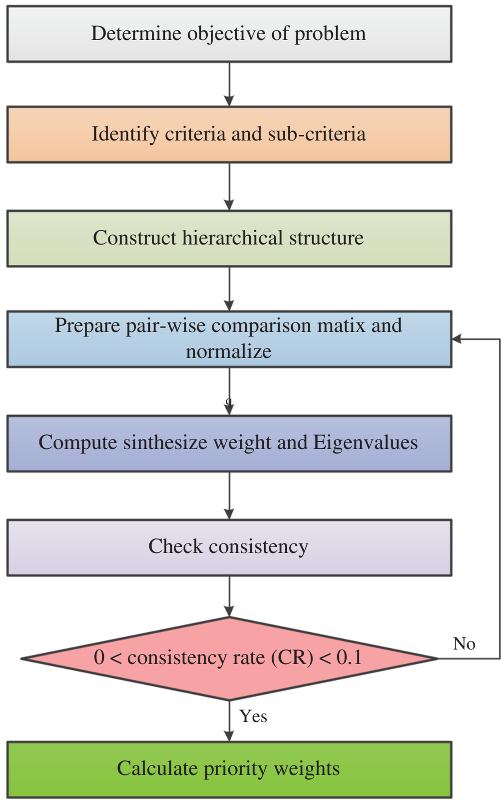

FIGURE 3 The flowchart of AHP method

2.1 | AHP and fuzzy AHP

The four main stages the AHP[33] are (a) setting up the system based on hierarchy by disintegrating the problem into a hierarchy of mutually coupled factors, (b) comparing weights among the features of the decision elements to develop the reciprocal matrix,[34] (c) create the individual independent judgment and estimate the relative weight, and (d) prepare cumulative of relative weights of the elements to decide the best options or policies. The flowchart for AHP method is illustrated in Figure 3.

The eigenvalue method of AHP[35] is used to handle crisp numbers whereas the linear-programming technique, the lambda-max technique, and the geometric mean technique are used to deal with problems in AHP employing fuzzy numbers. Kabir and Shihan[36] devised the AHP for assortment of RESs. Yi et al[37] explored an AHP method taking into account benefit, opportunity, cost, and risk (BOCR) to prioritize sustainable renewable-energy sources to cater energy demands for North Korea. Abdullah and Najib[38] have devised an FAHP method for sustainable energy planning and technology selection, to deal with the uncertainty in the decision-making problem. The life cycle assessment (LCA) and AHP methods are employed for the sustainability assessment of power plants in Mexico by Claudia et al.[39] The energy generation technologies have been evaluated for three different situations for Turkey using FAHP by Talinli et al.[40]

2.2 | ANP and fuzzy ANP

The ANP technique developed by Saaty[41] is found adequately suitable to address criteria those are exhibiting mutually dependent relationships or feedback sensitive. In general, ANP consists of AHP together with a feedback mechanism and uses a super-matrix to deduce the degree of influence of mutual interdependence.[42] The overall priority vectors can be computed given network configuration after transforming the super-matrix into the limiting powers or determining dependence and

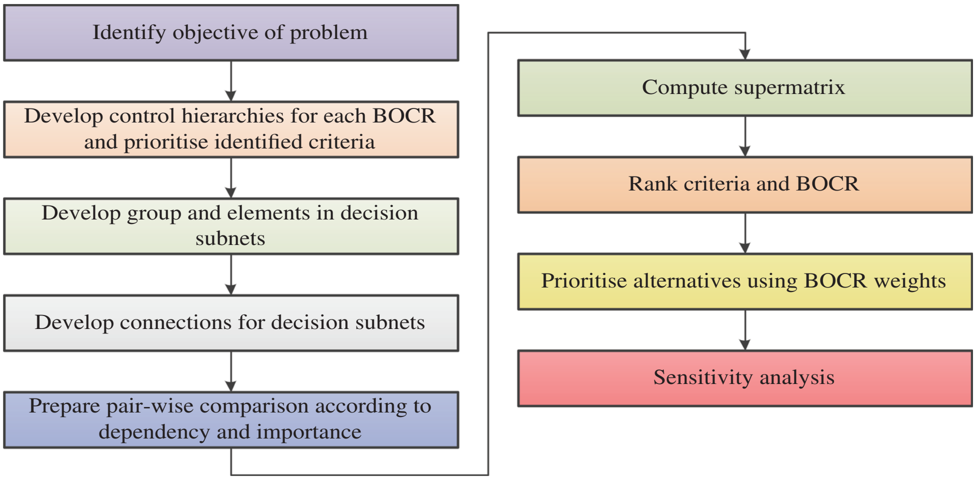

FIGURE 4 The flowchart of ANP method

feedback issues from set of criteria. Initially, the ANP is used to compare all criteria of system to form the supermatrix by preparing pair-wise comparisons. The relative significance score can be calculated on a scale of 1 to 9 for representing identical to intense importance.[33] The flowchart for ANP method is illustrated in Figure 4. In most of the applications, it is difficult for DMs to compare two criteria precisely having partial information and ambiguity involved. Hence, the fuzzy ANP is explored to expand the traditional ANP, and the fuzzy decisions are involved to compare the relative ratios of weights between criteria. Due to ambiguity involved in evaluating complex problems using the crisp ANP, the hybrid methods have proved more advantages, and hence, fuzzy numbers are more preferred for pair-wise criteria comparison, and overall fuzzy weights can facilitate DMs understand the uncertainty degrees of problems.

2.3 | Simple additive weighting method

Simple additive weighting method (SAW) can be considered to be the most simple, the most popular, and proven technique to handle MCDM problems because the preferences of DMs can be represented by the linear additive function.[43] Hence, SAW method can also be known as weighted linear combination or ranking method. Due to its simplicity of computation, it is the most widely used technique for solving MADM problems. The weighted performance ratings for each alternative for all considered attributes is computed in order to decide ranks of alternatives. Handling of attributes with very wide range of values is done through a method of normalizing the decision matrix into a scale, which can later be compared with all of the ratings of existing alternatives. The flowchart for SAW method is illustrated in Figure 5.

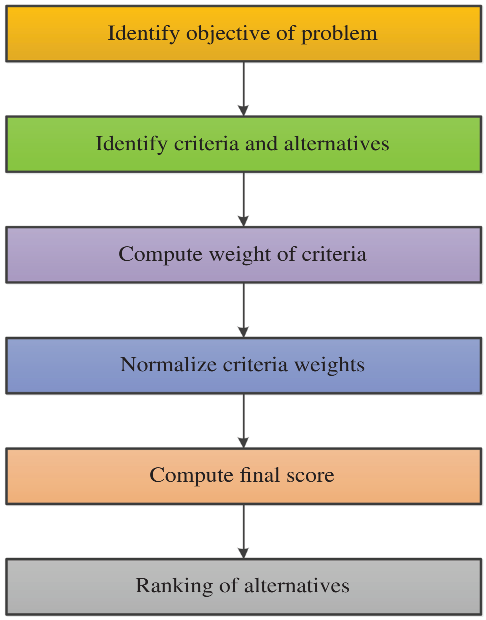

FIGURE 5 The flowchart of SAW

2.4 | Fuzzy MCDM

The fuzzy MCDM (FMCDM) was first introduced by Bellman and Zadeh in 1970[44] and now is used for selection of alternatives by DMs involving nonquantifiable criteria. The FMCDM has found its applications in diversified domains like evaluation of weapon system, planning in biotechnology technology transfer, design process optimization for vehicle components, blended energy supply decisions,[45,46] selection of urban transportation investment alternatives,[47] risk evaluation for tourist, assessment of electronic marketing methodologies in the information service industry, location selection for hotel or restaurant, and performance assessment for distribution-centers and warehouses in logistics industry.[48,49]

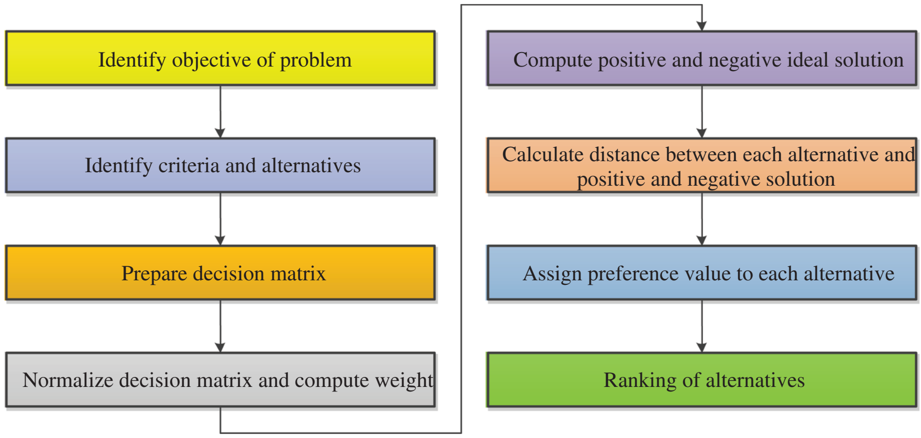

FIGURE 6 The flowchart of TOPSIS method

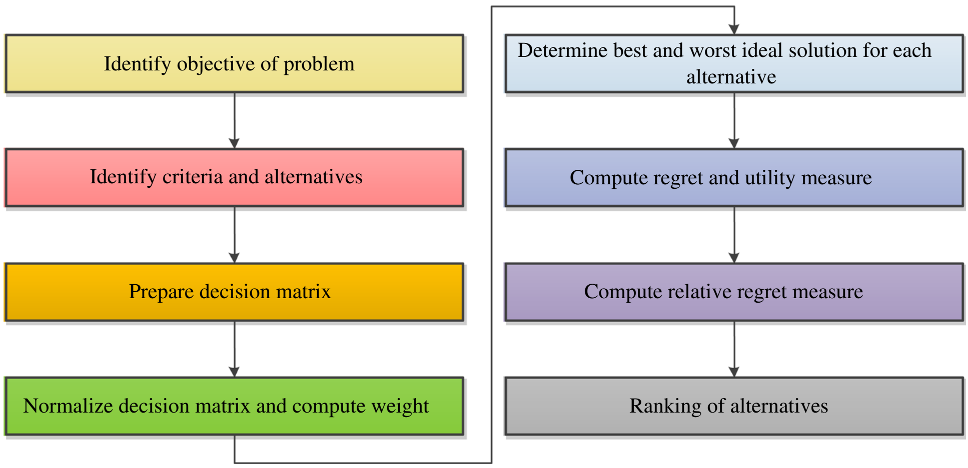

FIGURE 7 The flowchart of VIKOR method

2.5 | TOPSIS

Hwang and Yoon[26] proposed TOPSIS method in 1981 to find out the most feasible alternative depending upon the concept of the compromise solution defined as the solution with the minimum and maximum Euclidean distance from the ideal solution and the negative ideal one, respectively. The flowchart for TOPSIS method is depicted in Figure 6. Doukas et al[50] developed a linguistic TOPSIS model for sustainability assessment of renewable energy-based projects. The TOPSIS method in decision-making issues was extended to fit into fuzzy environment by Chen,[51] and according to this, the attributes could be transformed in Triangular Fuzzy Numbers. The normalization method can be used afterward for the distance measurement calculation for the deciding priority.

2.6 | VIKOR

The VIKOR method[52,53] was proposed for optimization of multiple criteria to determine compromised solutions for conflicting criteria of a complex systems. The VIKOR method is an efficient means in MCDM, mainly in situations wherein the DMs cannot decide preferences at the initial stage of project planning. After assigning the initial weights, it computes the negotiation ranking list and its solution and the intervals of weight for preference stability of the computed solution. This method explains prioritizing and selecting the best from a list of options involving mutually opposite criteria. It sets up the multi-criteria ranking index depending on the particular measure of “nearness” to the “ideal” solution. Quijano et al[54] analyzed VIKOR method in order to determine the most optimal combination of renewable energy resources for Columbia, wherein the model took into account around 5000 possible alternatives to identify the best one. The flowchart for VIKOR method is illustrated in Figure 7. Kaya and Kahraman[55] promoted an integrated VIKOR-AHP technique for the most favorable energy policy and generation site. A pair-wise comparison matrices of AHP were applied for computing the evaluation criteria weights. The renewable energy plan originated by the Spanish government for renewable energy project was evaluated by Cristóbal[56] using the VIKOR and the AHP technique. The fuzzy ANP-VIKOR is employed for site

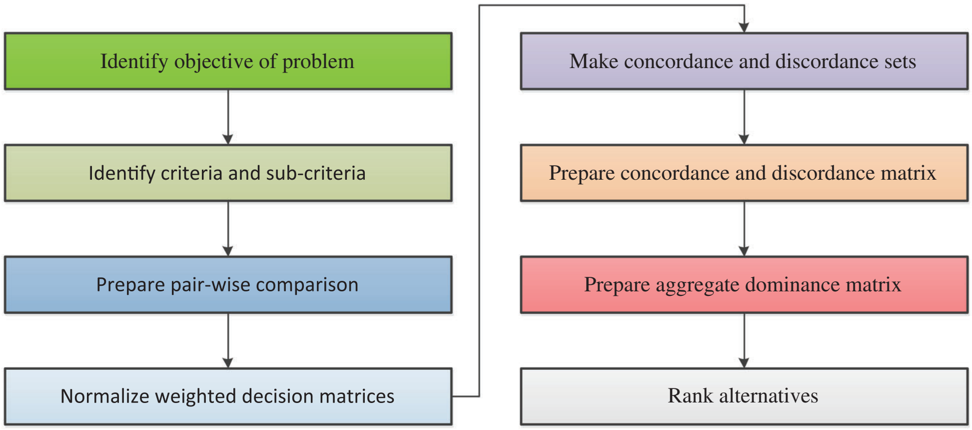

FIGURE 8 The flowchart of ELECTRE method

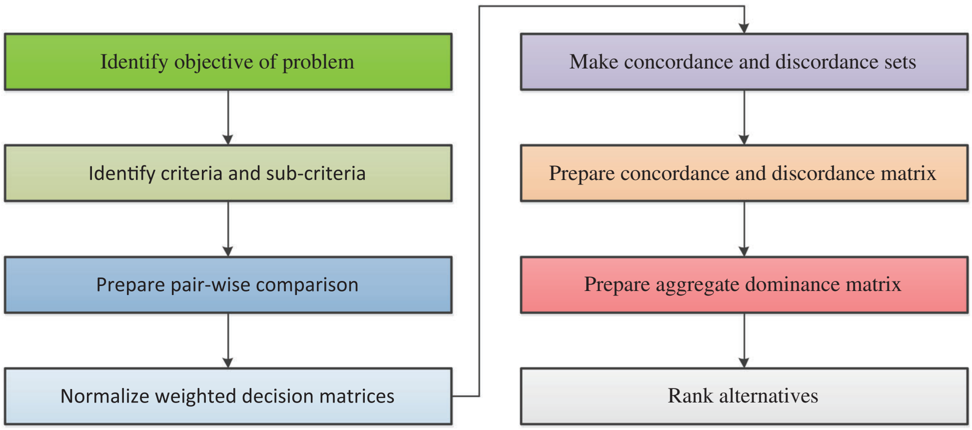

FIGURE 9 The flowchart of PROMETHEE method

selection decision framework for large-sized commercial rooftop PV system has been analyzed by Wu et al.[57]

2.7 | ELECTRE

The outranking associations concept was to introduce the ELimination Et Choice Translating REality (ELECTRE) method proposed by Roy (1968) and Benayoun et al (1966).[58] Since, then number of ELECTRE models have been evolved depending on characteristic of the problem objective in order to search for a kernel solution or to prioritize options, the significance of the criteria considered, and the preferential statistics (weights, concordance and discordance index, and veto effect). Beccali et al[59] applied the ELECTERE method to decide regional level for the distribution of renewable energy applications. The ELECTRE was evolved into ELECTRE I initially and improved later on to ELECTRE II, ELECTRE III, ELECTRE IV, ELECTRE IS, and ELECTRE TRI. They are used in the fields of business, development, design of small hydropower.[60] The process flowchart to rank alternatives using ELECTRE is presented in Figure 8.

2.8 | PROMETHEE

A group of outranking techniques, known as Preference Ranking Organization METHods for Enrichment Evaluations (PROMETHEE) for addressing MADM problems, were proposed by Brans et al.[61] These techniques encompass a simplification of the criterion conception. In this, a fundamental theory of fuzzy outranking relation is initially taken and constructed into each criterion using pair-wise comparison for alternatives to different relation-degrees in each other. The flowchart of PROMETHEE method is shown in Figure 9. The different dependencies are then considered to establish a partial preorder known as PROMETHEE-I, a complete preorder as PROMETHEE-II, or an interval order called as PROMETHEE-III on a fixed number of viable solutions. Moreover, a method, known as PROMETHEE IV, is developed for the problems wherein the group of possible solutions is continuous in nature.

The PROMETHEE applications include evaluation of alternatives for sustainable energy by Cavallaro,[62] assessment of energy technologies using modified version of it by Oberschmidt et al,[63] prioritizing alternatives for induction motors replacement using PROMETHEE II by Sola et al,[64] and selection the efficient energy system for regions and constructions by Virtanen.[65] Ren et al[66] has proposed a model using a combination of linear programming integrated with AHP and PROMETHEE techniques to developed optimal residential energy system for a standard setup of homes in Kitakyushu, Japan. The combination of traditional and sustainable energy solution is embedded to prioritize a group of alternatives against economic, energetic, and environmental criteria. Debbarma et al[67] devised a mechanism to figure out emission from different generation technologies using the AHP for the obtaining weights of criteria and VIKOR and PROMETHEE II to prioritize alternatives.

2.9 | Grey relation model

The theory of Grey system was proposed by Deng[68] and with a hypothesis of undefined system, and the systems can be characterized using available information to frame a relational analysis or to develop a model.[68,69] A grey relation space and a sequence of nonfunctional type models are characterized using Grey theory, which are found in this space to reduce the requirement for a large number of collected data in known numerical ways or the typical distribution and computation.[70] Celikbilek and Tuysuz[71] have proposed a grey-based MCDM model for the impact assessment of renewable energy resources from profitable, sustainable, societal, and ecological aspects. Chen and Tzeng[72] further attempted to combine the grey relation model depending on the concepts of TOPSIS to evaluate and select the most suitable alternative.

2.10 | COPRAS

Another MCDM technique known as COPRAS (COmplex PRoportional ASsessment) was developed by many in order to resolve various issues.[73] This technique has few merits over other techniques as follows: (a) It allows concurrent application of the ratio to the ideal-solution and the negative-ideal-solution, (b) simple and logical calculations as well, and (c) less time to obtain the solutions compared other more popular methods such as AHP and ANP. A comparative analysis of CORPAS with TOPSIS has been done to evaluate system priority for a given distributed energy systems comprising renewable and traditional energy sources and inferred that the results are obtained from both methods reasonably relevant and feasible.[74] The selection of the most effective RES among feasible alternatives using the CORPAS integrated with AHP was also proposed by Yazdani-Chamzini et al.[14] The other applications are site selection for wind farm,[75] hybrid wind farms,[76] evaluation of power plants,[77] etc.

2.11 | Fuzzy integral technique

A conception of a fuzzy integral was given by Sugeno and found its applications in the subjective evaluation of patterns and forecast estimation,[78] and an attempt has been made to express the fuzzy integral of a positive, quantifiable function, with respect to a fuzzy quantity.[79] The privileged independence can be defined as the preference result of an attribute over another which are not affected by the others. Nevertheless, in practical MCDM problems, the criteria behave usually mutually dependent. In order to address this noncumulative issue, the Choquet integral was explained by Choquet in 1953 and Sugeno in 1974.[80] Using the Choquet integral, a particular type of interaction between criteria employing the concept of redundancy and support or synergy can be characterized. It generalizes not only arithmetic mean and weighted mean but also ordered weightage aggregator (OWA) operators. On the contrary, the Sugeno integral generalizes median operators, weighted maximum, and weighted minimum.

Sugeno, in 1974 proposed the theory of fuzzy-integral and fuzzy-measure, simplifying the typical definition of a degree by replacing the typical cumulative property with a nonstrong constraint, that is, the property of monotonicity in terms of group attachment. A few concepts from the theory related to fuzzy integral and fuzzy measure was also illustrated by him. Heo et al[81] used FAHP to examine the evaluation parameters for assessment of renewable energy distribution application. Kahraman et al[82] suggested a comparative analysis for multicriteria selection among renewable energy options using fuzzy axiomatic design and FAHP. Lee et al[83] applied an FAHP approach to assign rank to the weights of hydrogen storage techniques from the aspects of hydrogen economy. Apart from identifying site locations for solar and wind farms, wave energy as another source of renewable energy has been explored by Wang and Chen.[84] They have employed FAHP and weighted aggregated sum-product assessment (WASPAS) techniques for identifying optimal location for wave energy plant along coastlines of Vietnam. In addition to general criteria for assessment, wave height, distance between waves and numbers, ocean depth, and turbulence are some of the significant criteria being involved in the study. Perera et al[85] have proposed a decision-making technique for developing scheme for hybrid energy systems using Fuzzy-TOPSIS (FTOPSIS) in combining multiobjective optimization.

Balezentiene et al[86] also explained a MCDM structure for prioritization of energy harvests using fuzzy-MULTI-MOORA technique, which ensures to handle ambiguous information.

Kaya et al[87] conducted a survey of MCDM techniques for decision-making and energy policy. An in-depth survey briefed various MCDM techniques and their various applications fields like, selection of energy sources, selection of power plant location, evaluation of energy projects, and determining energy policy especially in renewable energy sector utilizing AHP, TOPSIS, ANP, VIKOR, PROMETHEE, ELECTRE, and DEMATEL without fuzzy approach.[87]

The MCDM techniques are very common in the area of sustainable energy management and framing energy policy, including planning and allocation of energy resources.[88] The MCDM technique facilitates in providing solutions to problems, involving multiple objectives and contradictory criteria in energy planning decisions, and it employs different techniques aforementioned.

3 | APPLICATIONS OF MCDM TECHNIQUES

3.1 | Renewable energy policy planning and management

Nowadays, almost every country has been thrusting toward reframing of their energy policy, which is targeting integration of more and more RESs to protect globe facing environmental issues like global warming, depletion of ozone layer, irregular season patterns, more frequent storms, etc. This has become the need for new policy implementations by local government and international agency to counteract enormous exploitation of fossil fuels being used mainly for transportation and electricity generation across the world. Energy and environment are treated as two sides of a coin, and there is trade-off between energy policy planning and management, wherein none should be ignored. The MCDM techniques are found to be very effective means to develop an evaluation-based planning and management methodology, since it involves numerous constraints, and most of them are mutually conflicting in nature. It includes technical aspects like efficiency of generator and its life span, technology, and complexity of components, as well as economic indicators like capital cost, operation and maintenance (O&M) cost, cooling water requirements and charges if any, acceptance by the end users and distance of power plant from load centers. These parameters may be treated equally[89] or their scores should be derived from experts[22,90] who belong to diversified area of energy systems. For example, from a technological perspective and based on geographical locations, different RESs are found to be the most suitable ones, like solar is preferred for equatorial regions, like Iran,[91] Africa, India, Pakistan, whereas hydro would be the best choice[92] where topography is favorable and heavy rainfall is expected. Recently, due to tendency toward to improve sustainability and resiliency of system, more and more microgrid systems are showing its applicability. The planning of these microgrids also involves use of MCDM methods to identify and rank components of amalgamated resources.[93-95] Evans et al[89] has suggested sustainability parameters to evaluate renewable energy technologies. The parameters they have considered are generated electricity price, greenhouse gas (GHG) emissions for entire life-span of the technology being adopted, utilization of renewable sources, efficiency of energy conversion, footprint, water consumption, and social influence. In this study, each factor was considered to have identical significance to sustainable development and utilized to prioritize the renewable energy tools and their impacts. The challenges encountered by energy planners and other stakeholders associated with energy-intensive issues have been discussed by Diakoulaki[96] and Løken[97] employing many evolution and approaches of MCDM. The optimal design and planning framework for microgrids using multidisciplinary optimization approach using AHP and compromise programming has been investigated for reduction in GHG emission, energy cost, energy generation, and net-present-value to fulfill primary concerns of most of the stakeholders by DMs.[98]

Abotah and Daim[99] employed the AHP method to develop a model for the efficiency assessment of energy policy actions in order to promote renewable energy system.

The renewable energy policy-making framework for Iran and claimed to be equally applicable technique in developing strategic decisions on energy policy to other countries as well using BOCR and ANP as integrated approach was proposed by Alinezhad and Khalili.[22] The study was conducted to achieve the log-term vision to get at least 10% energy from RES by 2025 in Iran. The ANP model was extended to a hybrid model based on ANP and BOCR. The ANP-part used to enable the concurrent evaluation of quantifiable and subjective criteria by effective decision-making process. The BOCR analysis was employed to find Iran's energy demand–supply and the RE assessment criteria, and then the ANP analysis was employed to decide order of importance for the RESs against the considered criteria. In order to get opinions, they involved experts from diversified background, like environmental science, engineering, economics and management, technology, and policy experts having different education levels. While selecting any energy-sensitive project, it was derived that the technology is followed by economy, energy vulnerability, global effects and social welfare. The solar energy–based generation was proven to be the most attractive option, and among solar, hydro, geothermal, biomass, and nuclear RESs could be ranked with weights of 0.3, 0.2, 0.29 and 0.2 for benefits, opportunities, cost and risk, respectively.[22] A comparative analysis of ranking RESs for electricity generation was carried out by Hsing-Chen Lee in Taiwan using different MCDM methods, such as WSM, TOPSIS, ELECTRE, and VIKOR.[92] In order to assess the significance of each criterion for the positioning of RESs, the Shannon entropy weight technique was applied. The weights estimation results were found to have the first priority in all assessment criteria, followed by employment opportunity, operating, and maintenance cost. The ordering of options indicated that hydro is identified as the most promising source of energy in Taiwan, followed by solar-based, wind farm, biomass, and geothermal based. It was concluded that hydropower is the best RES option due to having the most matured and inexpensive technology in Taiwan. Four dimensions, namely financial, technical, environment, and social were taken into account in the same study. In sensitivity analysis, five scenarios were worked upon, one case wherein the dimensions were given equal importance and other four cases wherein any one is prioritized over others. The solar was considered the best choice for being socially important and with all having equal importance due to its apparent less destructive impact on environment and matured technology. The wind could be the other option due to low-carbon emission feature and hydro from economic aspects due to mature technology. It was concluded that efficiency was the most important criterion, and solar and wind integration could offer utmost technical advantages due to Taiwan being second largest solar PV producer in the world.[92]

A hybrid COPRAS-AHP methodology was developed to identify the most beneficial renewable energy plan by Yazdani Chamzini et al[14] and claimed to facilitate reduction decision failure risk by DMs. The integrated approach was suggested, wherein AHP was used to calculate the weights of evaluation criteria, and COPRAS was incorporated to arrange the existing alternatives in best to worst order. After comparison with MCDM methods like, SAW, TOPSIS, VIKOR, MOORA, and ARAS, it was concluded that the method outperformed over those for given three different cases. Moreover, based on wind, solar, biomass, and bio-fuel as RES, out of 13 alternatives, power generation, operating hours, life-cycle, and tons of emissions of CO_2 reduction per year (tCO_2/y) were treated as benefit criteria and investment ratio, execution time, operation, and maintenance cost as cost criteria.[14] The interval-valued hybrid technique employing AHP and TOPSIS is developed to identify the most promising renewable energy in Taiwan by Chou et al[100] This integrated approach helps to mitigate impact of ambiguity, uncertainty, inconsistency, and incompleteness present in experts' opinion. With this approach, hydro power was found to be the best option followed by solar-, wind-, and biomass-based energy sources.

In recent years, studies have shown that identification of better prospects in the area of energy management[101] is emphasized in order to achieve the target of reduction in energy consumption.[102] Since, improving the efficiency of today's requirements is more practicable than boosting production capability to cater future energy needs. The energy efficiency is directly mapped to specific energy consumption in manufacturing industries. This is also interpreted by the national standard of China, as the ratio of the yield of products and services to the power consumed.[103] There are three possible means to improving energy efficiency or reducing consumption through: (a) careful management, (b) integrating better technologies, and (c) implementing better policies and regulations.

The effectiveness in policy-making of conventional building energy management system for improving building-level energy efficiency having dynamic temperature set points using AHP as MCDM method has been investigated by Ferreira et al.[104] They proposed a different hierarchy of decision-making based on the selection of technologies for an efficient management of energy consumption for the establishments through decision process for selecting technologies to support energy management.

An application of SMART[105] was demonstrated for a sample distribution network for an existing distribution network of a Distribution Company (DISCOM) in the United Kingdom. The analysis serves quite helpful in evaluation of all scheduling difficulties and substantial benefits to a DISCOM as well. In this study, 1728 possible solution configurations were operated upon which criteria (weights assigned) are annual energy losses (6), system security (5), supply availability (5), capacity constraints (9), environmental impact (8), and investment cost. Moreover, anticipating escalation in future load demand, various annual load growth scenarios with 1%, 1.8%, and 2.7% are also investigated. It was concluded that this study not only assists in terms of improving the interest of feasible options but also contributes by possibly deferring network investments.[106] Rojas-Zerpa and Yusta[107] suggested hybrid AHP-VIKOR techniques to develop a mechanism for the assessment of electricity network in remote rural areas and employing more than 10 alternatives.

An interesting fact was established that expansion of grid and distributed or decentralized systems designed with solar energy and storage devices such as batteries (residential) is not an only alternative for rural electrification program when processed using MCDM technique. However, compact decentralized power supply alternatives could offer their best in electrification framework of small rural and remote village when a hybrid approach, AHP, and VIKOR methods of MCDM is employed.[107] Such system could represent distributed generation or microgrid system. The microgrid is typically integrated with various types of distributed resources, which facilitate improving energy efficiency and relieving the undesirable influence on power grid. An optimized combination of source selection has been explained by Bohra et al[93] using AHP-based MCDM technique for microgrid planning (Table 1). An extensive and detailed analysis was conducted to rank blend of alternatives for grid-interactive microgrid system. Along with utility grid, the energy sources considered were solar photovoltaic (SPV), diesel generator, BESS, and combined heat and power with absorption chiller (CHPC). A similar analysis

TABLE 1 Applications of various MCDM techniques in renewable energy policy planning and management

Method(s)	Primary attributes	Rank	Secondary attributes (rank)	Computed rank
Shannon's entropy weight[60,92]	Finance	2	Investment cost	9
			O&M cost	3
			Electric cost	6
	Technology	1	Efficiency	1
			Capacity factor	5
			Technological maturity	8
	Environmental	3	GHG emission	7
			Requirement of land	4
	Social	4	Job creation	2
			Social acceptance	10
AHP[93]	Economical	1	Initial cost	1
			Cost of energy	2
			Internal rate of return	3
			Maintenance expenditure	4
	Operational	3	Efficiency	1
			Number of operating days	3
			Energy generation	2
			Forced outage rate	5
			Capacity utilization factor	4
	Technical	2	Requirement of local skill	2
			Self-sustainability	3
			Fuel availability	4
			Generation capacity	1
	Structural	5	Foot print	3
			Life span	1
			Modularity	4
			Installation lead time	5
			Annual performance index	2
	Others	4	Noise	3
			Pollution (CO_2) emission	1
			Aesthetics	4
			Stakeholder preference	2

was done by Banerjee and Majumder[108] for selection of sources in microgrid using AHP as MCDM method. The three primary criteria taken were financial liability, geographical suitability, and design constraints, and associated sub-criteria were initial cost, cost of replacement, operation and maintenance cost, efficiency, lifetime, payback period, duration of resources, distance from grid, and minimum space required. It was concluded that the key parameter was payback period and the least significant was cost of replacement. Zhao et al[109] discussed a different hybrid MCDM technique integrating the best-worst method (BWM), the entropy weighting approach, and grey CPT for optimal selection of microgrid planning projects. The initial evaluation index system comprised around 18 sub-criteria and was developed from the perceptions of economic, reliability of electrical supply network, and protection for environmental, then the weights of sub-criteria were found integrating the qualitative weights derived from the BWM and the objective weights calculated using the entropy weighting method, and lastly CPT was employed to combine with Grey theory to select the most suitable planning of micro-grid project. The microgrid can be operated in either grid-interfaced or independent mode, operating on relatively different strategies. Reliable and actual islanding is essential in order to ensure optimal operation of microgrid.[95] The feature of microgrids as offering effective auxiliary services (to the power utility) was explored by Contreras et al[94] using probabilistic multiobjective microgrid planning methodology. The planning strategy was based on the best possible size and location of distributed energy resources in order to reduce inconsistent power in islanding condition, while to improve remaining power for ancillary services facility and mitigate the expenditure and operating costs of the microgrid in grid-assisting mode, respectively. The methodology was verified in an adapted PG&E 69-bus distribution system employing the nondominated sorting genetic algorithm II (NSGA-II) optimization technique, and an AHP for decision-making was applied to address the optimization problem. The planning technique was focused on the technical optimization of ancillary services supply instead of the economic aspects. It was suggested that the probabilistic multiobjective microgrid planning could be used to assess planning under variety of market situations, networks, and study cases to evaluate open market features for enhancing cash flow of microgrid.[94]

A suitable technique for evaluating and selection of the anti-islanding techniques for grid-interactive SPV system application using MCDM analysis was examined by Datta et al.[110] The various crucial factors, which dominate the selection of anti-islanding methods for evaluating criteria, have been assessed using the ANP and criteria preferences using decision matrix of the TOPSIS distance–based optimization technique.[110] For selecting the best option in distributed generation (DG) planning, the AHP method has been used based on various combination and configuration information fetched from HOMER software.[111] This process does not only take care of technical constraints of DG units but also the effects of the uncertain parameters such as robustness, flexibility, risk exposure attributes, fuel cost, load growth, and wind speed.[112] Creating an electrical facility for an island is a challenging task because in most of the scenario, the electricity demand of an island should be catered by harnessing available resources if grid extension is practically not feasible or uneconomical. The scope of various MCDM techniques mapped with criteria and indicators in energy planning using has been presented by Wimmler et al.[113]

3.2 | Applications in solar photovoltaic systems

The selection of solar farm location is one of the most requisite concerns and judicious decision to be taken by DMs. It is not only about availability of sufficient sunshine over the year and irradiation level at given location but also involves a blend of economical perception and sustainable goals for particular region. Nowadays, manufacturing process and efficiency of commercial solar cell have improved dramatically due to extensive research and hefty manufacturing investment.[114] Being modular in nature, the solar farm size may range from few kW to multi-MW (such as the world's largest PV farms named Tengger Desert Solar Park in China with capacity of 1547 MW[115]) and may span few to tens of hectares. To this end, site identification requires a meticulous and systematic analysis. China, the United States, Japan, Germany, India, Italy, Australia, the United Kingdom, South Korea, and France are major countries that have large projects to harness solar energy by installing solar PV farms, and many are under construction or planning. The selection of unsuitable sites for solar farm may result into underutilization of tapped energy and resources. Moreover, it involves numerous dimensions viz, technical, economic, environmental, social, and political. Additionally, each dimension has its relevant sub-criteria of their own significance governing size of farm, distance from transmission line (for grid-connected) and distance from local load center under independent entity, acceptance by locals and prevailing political stability and energy market, topography and accessibility from main roads, impact on natural habitat of wild-life, regulations and norms on carbon emission, etc. in the given region/country. Most of the researchers preferred to use AHP for analysis and calculation of weights of factors[116-119] and TOPSIS method to evaluate all possible alternatives based on degree of adequacy,[117,120-124] AHP-ANP,[125] ANP-DEMATEL,[126] ELECTRE,[127] and PROMETHEE[128] methods. The use of GIS helps to confine the area of interest by eliminating zones which prevent the implementation of renewable energy plants having constraints or restrictive criteria.[117,122,124,126,129] Hence, it is exceptionally important to identify and rank viable locations for deployment of solar-based generation which incurs a huge investment. In some literature, researchers have revealed the global weights or ranks for criteria considered as shown in Table 2.

Though many researchers prefer AHP method for weight assignment along with other techniques such as fuzzy-based TOPSIS or ELECTRE or VIKOR to improve project evaluation, a few have carried out suitability assessment for solar site using ELECTRE, ANP, and PROMETHEE. Furthermore, geographic information and other infrastructural details are fetched using GIS. Based on assessment of criteria done by almost every group, it is seen that climatology/technical and associated sub-criteria are given utmost importance; solar irradiation being the most essential followed by average temperature and humidity factors, respectively. Exceptionally, a prevailing political situation may also be an influential factor in a few region, and subsequent ranks are given to technical and economic factors, followed by environment and the least to social aspects.[120] Some literature do not mention the ranks for the considered criteria.[117,125,127-130] Moreover, number of literatures highlighted that the distance of solar plant from residential area, roads, and nearby transmission lines also should not be overlooked to decide potentials for solar farm.[121,124,126,131] It is obvious that different authors have their own inclination and perspective, but besides solar density of given locations, the vicinity around load centers, minimum distance from roads to ensure minimum installation time and ease of erection, prevailing political situation, government policies, and stability play a vital role. In addition to these, the goal to become self-sustainable and adoption to green technologies should be considered.

An AHP method was adopted for ranking of 5 criteria, 20 sub-criteria, and 4 alternatives for renewable energy focused planning for rural areas in the Caribbean region of Colombia. From the opinions collected from experts, solar energy was found the most promising RES, and technical aspect is the most sensitive followed by environmental, social, economic, and risk factors.[119] Tunc et al[122] identified 10 key factors for the installation of the solar power station location in Istanbul. These key parameters were weighted using AHP method. These key parameters were then compared with the weights derived by evaluating the results to determine important factors for site selection. After computing the weights, the significant data are collected, and the required analyses are carried out using the GIS, and the most appropriate locations are prioritized as solar-based generating site for Istanbul.[122] The purpose of the Uyan's[129] study was to select the most favorable locations for solar farms by using hybrid approach of GIS with AHP. The criteria considered in his study to examine the promising sites were distance from transmission lines, distance from load areas, land utilization, distance from roads, and slope. The AHP technique was applied to evaluate the importance and determinate weights of criteria, and it was determined that land utilization had the highest significance, followed by proximity to supply grid and residential load areas, respectively.[129] Merrouni et al[124] evaluated the suitability of the Eastern region of Morocco to install utility-scale CSP plants using hybrid method using GIS and the AHP. A GIS database with high spatial resolution was constructed using layers provided from different authentic government sources. The potential of the direct normal irradiation (DNI) was found to be the most influencing criterion for CSP site selection; Eastern Morocco could be chosen as the most suitable location for installing CSP power plants. The feasibility of location for the installation of CSP plants was computed by integrating the GIS and the MCDM for the dry and wet cooling scenarios as well. It has been concluded that direct normal irradiation was found to be the most important criteria followed by slope irrespective of type of cooling, and Eastern Morocco was considered as a preferred site to install CSP power plants with a proportion of 5.5% and 11.7% for the dry and the wet cooling, respectively.[124] Tahri et al[116] have studied location, climate, orography, and land requirement as the most dominant attributes governing the location for utility-scale solar farm in Sothern Morocco. In this analysis, AHP was used to compute the corresponding weights of criteria. It was concluded that the climate was the most important criterion since it governs the potential electricity production for solar farm followed by orography as steepness plays vital role in particular area.[116] SolarGIS maps and few ArcGIS tools were integrated with BWM as MCDM method to identify potential sites and found north-western part of Beijing, China, the most appropriate for large-scale solar PV projects with nearness to urban areas, accessibility to transportation network, accessibility to power transmission lines, availability nearby water resources, and slope criteria.[132]

Sindhu et al[120] attempted to use AHP-TOPSIS analysis for site selection problem for SPV in state of Haryana,

TABLE 2 Applications of various MCDM techniques in solar PV projects

	Primary attributes	Secondary attributes (rank)	Computed rank
AHP-fuzzy TOPSIS[120]	Social aspect	Impact on agriculture, employment, and tourism, impact on economic development in vicinity region, public acceptance, Nearness from residential area	5
	Technical aspect	Availability of solar irradiation data, skilled manpower availability, climatic conditions	3
	Economical aspect	Infrastructural cost, Transmission grid accessibility, Road and rail accessibility	2
	Environmental aspect	Visual impact, impact on wild life and endangered species, noise impact, harmful toxic emission	4
	Political aspect	State government policies, regulatory boundaries, land acquisition, resettlement, and rehabilitation	1
GIS-AHP[117]	Environmental	Slope	N/A[a]
		Land aspects	N/A
		Proximity to urban area	N/A
		Proximity to roads	N/A
		Proximity to power lines	N/A
	Technical	Solar irradiation	N/A
		Air temperature	N/A
AHP, ELECTRE, TOPSIS, and VIKOR[130]	Solar energy potential	N/A	N/A
	Allocated feeder connection capacity	N/A	N/A
	surface slope	N/A	N/A
AHP-fuzzy VIKOR[121]	Economic	Cost of land (1)[b]	2
		Infrastructural cost (2)	N/A
		O/M cost (3)	N/A
		Electricity demand (4)	N/A
	Environmental	Flat terrain and without trees region (2)	4
		Wildlife and habitat (3)	N/A
		Carbon emission savings (1)	N/A
	Social	Public acceptance (3)	6
		Employment opportunities (1)	N/A
		Effect on local economic development (2)	N/A
	Location	Distance from domestic load pockets (3)	1
		Accessibility to roads (2)	N/A
		Distance to on-grid transmission (1)	N/A
		Population density (4)	N/A
	Climate	Solar irradiation (1)	3
		Relative humidity (2)	N/A
		Annual air temperature (3)	N/A
	Orography	Elevation (3)	5
		Slope (2)	N/A
		Orientation (1)	N/A

(Continues)

TABLE 2 (Continued)

	Primary attributes	Secondary attributes (rank)	Computed rank
GIS and AHP[122]	Solar irradiation	N/A	1
	Sunshine duration	N/A	1
	Temperature ratio	N/A	5
	Land use	N/A	2
	Distance to other renewable energy plant	N/A	9
	Distance to North Anatolian fault	N/A	6
	Distance to objectionable and prohibited areas	N/A	7
	Wind speed	N/A	8
	Distance to energy transmission lines	N/A	4
	Slope	N/A	3
ELECTRE-TRI[127]	Environment	Agrological capacity	N/A
	Orography	Slope	N/A
		Orientation	N/A
		Plot area	N/A
	Location	Distance to main roads	N/A
		Distance to power transmission lines	N/A
		Distance to residential zone	N/A
		Distance to nearby substations	N/A
	Climatology	Solar irradiation	N/A
		Average temperature	N/A
AHP-ANP[125]	Political risks	Macroeconomic (change in energy policy), urban planning (approval from local body and construction license)	N/A
	Technical risks	Plant location, Technology	N/A
	Economic risks	Plant exploitation, plant location, plant start-up permits, technology, macroeconomic (bank financing, power demand, price of money and energy price)	N/A
	Time-delay risks	Connection to electric grid, urban planning	N/A
	Legal risks	Legal issues, connection to electric grid, urban planning (legislative changes in EIS)	N/A
	Social risks	Plant exploitation and urban planning (social consequences)	N/A
GIS-AHP[129]	Environmental parameters	Distance from residential load zone	N/A
		Requirement for land	N/A
	Economic parameters	Nearness from roads	N/A
		Site slope	N/A
		Distance from power transmission lines	N/A
GIS –AHP[124]	Climate	Direct normal irradiation	1
	Orography	Slope	2

TABLE 2 (Continued)

	Primary attributes	Secondary attributes (rank)	Computed rank
	Location	Distance from load center	3
		Distance from road and railway network	5
		Distance from supply grid	4
	Water resources	Distance from nearby water body	5
		Distance from dams	6
		Distance from underground water network	7
PROMETHEE[128]	Resource criteria	Sunshine hours per year	N/A
		Direct normal irradiation (DNI) ($MJ/m^2/y$)	N/A
		Average temperature	N/A
	Economical criteria	Levelized cost of energy evolution	N/A
	Infrastructure and construction criteria	Ease for grid connection	N/A
		Water supply accessibility	N/A
		Transportation accessibility	N/A
		Soil composition and the geology	N/A
		Land occupancy	N/A
	Environmental criteria	Impact on the nearby environment	N/A
		Benefits against reduction in pollutant emission	N/A
	Social criteria	Influence on the local economy	N/A
		Public support	N/A
GIS-ANP DEMATEL[126]	Environment	Agrological capacity	6
	Orography	Slope	7
		Orientation	9
		Area	4
	Location	Distance to road ways	5
		Distance to power transmission lines	9
		Distance to local load centers	3
		Distance to substations	8
	Climatology	Solar irradiation	1
		Average temperature	2

[a]Not available.
[b]Number in parenthesis indicate rank in respective criteria.

India. In this study, they considered five vital aspects (STEEP factors) and 18 sub-factors for assessment of solar farm in India. The AHP methodology was used to rank on the basis of weight values received from experts pair-wise comparison. The sensitivity analysis has also been carried out to extend and observe impact in terms of reliability and robustness evaluation of criteria. Around five potential sites were identified in Haryana for solar power projects according to identified STEEP factors and experts' score. The database of NASA was employed for relative solar irradiation, humidity, air temperature, and daily sunshine hours. In order to suppress the ambiguity involved in experts' score, fuzzy TOPSIS methodology has been suggested. It was concluded that from selected five locations, city of Sonepat was found to be the suitable site-location for to establish solar project of Haryana state in India.[120] Sánchez-Lozano et al[131] also explained the methodology to identify the most suitable locations for SPV farms in the South-eastern part of Spain. The AHP was used to assign weights of criteria for selected sites;

GIS was used to discover the suitable locations to build SPV farms by involving restrictions and factors into account. Then, the potential sites were studied and categorized using both TOPSIS and ELECTRE-III. A comparison between them was made, and similarity was observed having different results.[131] A similar case study was also presented to solar-farm site selection using GIS-AHP for South-Eastern Spain by Sanchez-Lozano.[123] An integrated MCDM framework was suggested addressing a plan selection for the shopping mall PV employing DEMATEL and ELECTRE III.[133] The interdependence and self-effect associations among criteria have been observed using DEMATEL technique and establishing the influential network relation map (INRM); out of 10 criteria, solar irradiation was identified as the most fundamental parameter followed by average temperature and distance from village for given site.[126] Sánchez-Lozano et al[127] used a GIS in order to decide the best potential site for solar PV farm project in the jurisdiction of Municipality of Torre Pacheco in south-eastern region of Spain. The plots were categorized according to multiple assessment parameters, by developing a multicriteria model and applied the ELECTRE-III method using the Decision Support System IRIS. The integration of GIS and IRIS facilitates the user opportunity of using the information fetched by the GIS mapping to evaluate multiple, conflicting and inadequate evaluation criteria. The GIS furnishes a cartographic and alphanumeric database into restrictive and criteria oriented. The limitations of using GIS layers which are defined from the current legislation like urban and undeveloped land, protected habitats for birds, public places, infrastructures, etc., to confine unsuitable area for solar farm installation. The criteria are organized into a hierarchical order from higher to lesser capacity of installation. These criteria are introduced into the GIS considering environmental, weather, location, and terrain evaluation aspects. The main advantage offered by integrating GIS and ELECTRE-TRI is GIS is used to collect and organize the information, which is to be fed to the decision support system (DSS).[127]

Aragonés-Beltrán et al[125] described about the Spanish firm that operated in the electricity market and has to decide on the excellent PV project among four alternatives to invest aiming maximum security. The impact between risks and alternatives was examined and evaluated using ANP. A hierarchical model consisting AHP for particular ANP and a network model were used. It has been recommended that the single network model can deal with all necessary information of realistic problem with strengths and weaknesses of ANP.[125] Four different locations across Spain represented alternatives with unequal capacity, voltage level and associated attributes were evaluated using 50 criteria.

Al Garni and Awasthi[117] discussed various applications of MCDM relevant to solar PV and CSP across number of locations of the world and considered model for Saudi Arabia taking into account various perspectives, such as economic and technical factors, with the objective of promising the optimal power generation at minimum project investment. An AHP was used to weigh the criteria and calculate a land suitability index (LSI) to evaluate potential locations. The LSI model categorized sites into: (a) minimally appropriate, (b) marginally appropriate, (c) acceptably appropriate, (d) highly appropriate, and (e) most appropriate. The overlaid result map showed that around 16% of 300 000 km^2, the area under study was having potential and suitable for installing utility-scale PV power plants situated mostly in the north and northwest of the Saudi Arabia. In the study, around 80% of the suitable areas were found to have an adequate to high LSI. The GIS-assisted MCDM methods were used to systematically take care of rich geographical information data and huge area as well as manipulate criteria significance for development of the most potential sites. The solar analyst modeling in ArcGIS was employed to generate solar irradiation details, and actual temperature measurements were collected from sensors placed at number of strategic places in the country, and the average yearly temperature is computed in ArcGIS. The site selection has been evaluated for equal and unequal weights for two primary criteria.[117]

Akkas et al[130] presented optimal site selection for SPV power plant problem in the central part of Turkey. The results showed comparison with the TOPSIS, AHP, VIKOR, and ELECTRE methods. The cities of Konya, Nevşehir, Aksaray, Karaman, and Niğde from the Central Anatolian Region of Turkey were chosen to carry out the study. And Karaman has been identified as the city with the best potential for solar power plant installation employing all of the techniques.[130] Solangi et al[121] discussed the problem for selection of the most appropriate location in Pakistan for solar PV power plan using AHP-fuzzy VIKOR as MCDM method. In the study, 14 potential cities were considered as alternatives and location, climate, economic, environmental, orography, and social criteria and associated around 20 sub-criteria. In the primary stage, AHP method has been applied to rank each of the main criteria and sub-criteria, and in subsequent stage, fuzzy F-VIKOR technique has been employed to prioritize the 14 alternatives. Based on results Khuzdar, Badin, and Mastung were found the most promising cities for the installation of SPV power projects in Pakistan. The sensitivity analysis was also carried out to reveal that attained solutions were consistent and robust for the installation of SPV power projects in Pakistan.[121]

In a parabolic trough concentrating solar power plant (PT-CSPP) system, the Sun's energy is concentrated by parabolic trough (PT)-shaped linear concentrators onto a heat absorber tube carrying fluid at 293°C to 393°C running along above the curved mirrors. As per available data of 2018, 90% of the CSP in commercial operation is trough.[134] Presently, PT technology is one of the least-expensive CSP options for electricity generation. Parabolic troughs are the most mature CSP technology with over a half gigawatts operating system across the globe. Department of Energy (DOE) also provides substantial financial assistance for solar research and development (R&D) in PT systems because CSP technologies can help in fulfilling the future objectives.[135] Wu et al[128] presented the study employing an combination of PT-CSPP site selection as a case study for China using Fuzzy PROMETHEE II approach integrated with a triangular intuitionistic fuzzy generalized ordered weighted averaging (TIFGOWA) operator. The three steps involved in achieving the objective were: (a) the triangular intuitionistic fuzzy numbers (TIFNs) were incorporated to realize indefinite knowledge, (b) the TIFGOWA operator was taken into account to compute the interaction problem involved in various assessment in deciding on alternative rankings and criteria weights of DMs, and (c) fuzzy PROMETHEE II method was discussed to prepare list of priority for the options by computing preference functions and assigning parameters for each criterion. The five major key aspects considered in analysis are economy, resource, environmental, infrastructure and construction, and social ones. The sensitivity analysis and comparative analysis were also conducted to confirm the viability of developed framework. The final ranking showed that one of the five alternatives, the Golmud city situated in Qunghai, was identified as most optimal site and Hami city as least suitable one.[128]

3.3 | Applications of MCDM in wind energy–based systems

In the last two decades, many countries have either framed new or revised their existing energy policies in order to emphasize the utilization of renewable energy–based generation. However, policy-makers involved always have been facing problems in selecting the most desirable options with conflicting criteria for energy and environmental policy, as they cannot be evaluated separately due to mutual impacts. From technical, environmental, and social aspects, wind-based electricity generation is shown to be one of the most competitive ways of generating electricity among other renewable contenders, viz. solar, biomass, hydro, tidal, etc. setting up large power plants. In wind energy–based generations, a number of wind-turbines ranging from few kWs to MWs could be deployed and expanded to meet load demand by forming wind farms. Besides, selecting the right number of wind turbines (ie, power capacity) and their sitting (ie, site selection) are the most important factors involving technical, economical, social, environmental, and political aspects. In such type of analysis, MCDM-based assessment is an attractive solution for obtaining an integrated decision-making result.

As applicable to other conventional type of power plants, technical parameters of wind turbines and essential equipments decide the suitability for electricity generation, and the land topography affects turbine type, design, and its size. In addition to that, its operation with grid or islanded condition and distance from nearby transmission lines also play vital roles in establishing wind farms. Apart from huge impact of initial investment cost and electricity market, government policy scenario also affects the size of wind farms to a considerable extent. Additionally, impact on environment, acceptable noise level, consequences on wild life near to wind farm, inclination, and acceptance by people are other influential factors which equally need attention by DMs. In identifying the most feasible location for wind farm, researchers have tried a number of MCDM techniques, the most common ones are AHP,[136-140] FAHP,[141,142] EELCTRE, and PROMETHEE techniques.

The AHP method was employed for assessment of the weights of criteria for determining suitability of wind farm location, and the weighted linear combination (WLC) method was used for identification of suitable sites in ArcGIS for South-Eastern Poland[140] where environmental, social, spatial, and technical criteria were taken into account. Likewise, a case study for Lesvos island of Greece was conducted in Reference 136 using AHP in association with GIS considering 11 various constraints in three different zones and energy demand for different load sectors, like domestic, industrial, commercial, agricultural, public, and municipal. The improvement in reliability of experts' judgment was investigated for a case study of Nigeria, wherein an interval type-2 FAHP was blended with GIS to assess the most potential location for wind farm. The wind speed, proximity to towns, proximity to grid access, slope, and proximity to roads were considered in the economic and technical assessment and rivers and water bodies, protected habitats for birds' species, and transport facility like airports to address environmental and social constraints.[142] The AHP with GIS is used to identify the most appropriate site for utility scale wind farm in the state of West Virginia by Ajanaku et al[143] A similar investigation was carried out by Kumar and Sinha for land suitability for wind farm for the state of Indiana using GIS and AHP.[144] The significance of these studies is critical wildlife habitat for birds is also considered as elimination criterion in AHP. Though, upto 2015, the fossil fuel price in Iran was lowermost in the world, but then the Iranian government was thinking of eradicating the subsidy provided for fossil fuel, and due to this decision, the oil price was increased. Such unprecedented step of government encouraged the investment in renewable-based generation. Noorollahi et al[145] addressed a GIS-based MCDM method to estimate the potential of wind energy resources in Markazi province of Western Iran. The criteria investigated were economic, environmental, technical, and geographic aspects, which were weighted equally. The analysis showed that 28% of the study area had potential for utility-sized wind farms projects. The environmental sub-criteria include mainly distance from highways and roads, railways, airports, electric power lines, ancient and cultural monuments, river, coast lines, wetlands, lake, water bodies, and environmental protected area; and physiographic considers digital elevation model and slope.

Lee et al[137] explained MCDM model, based on the hybrid AHP-BOCR, for site selection for wind farm project. Several factors influencing the realization of wind farm operations were investigated after collecting views of experts, and a performance ranking of the wind farm locations was derived. AHP assisted with BOCR is implemented in their study to take into account such type of mutually contradicting criteria in public-oriented projects. The selection of best wind farm location is governed by primarily business drivers, performance, and socio economic requirements. Based on these key factors, BOCR merits were identified. The benefits merit comprised site advantage, wind potential, and wind energy generation (WEG) function criteria; opportunities took into account financial benefits, policy nature, and matured technologies; cost considered wind turbine, connection, and foundation; and risks consisted concept conflict technical risks and improbability of land. The highest and lowest weights were computed for wind availability of benefits merit and technical risks of risks merit, respectively.[137]

Sánchez-Lozano et al[141] discussed the application of MCDM method for wind farm site selection in Southern-Eastern Spain wherein an FAHP was applied to derive the weights of the criteria, whereas the FTOPSIS was used to evaluate the alternatives. A process described that how qualitative criteria could be addressed together with quantitative criteria using fuzzy MCDM approach for assessment of potential wind farm sites. A GIS was employed to fetch the database of the alternatives and criteria, which were then transformed into a fuzzy decision matrix with the help of TFN. The coast of the Murcia Region, situated at the South-Eastern part of Spain, was selected for the area of study to carry out priority ranking of 10 alternatives. A fuzzy-AHP survey was conducted for collecting experts' score. The sensitivity analysis highlighted that the best solutions were not dependent of the criteria weights influencing the decision. In addition to that, a comparison was carried out with other fuzzy MCDM methods like fuzzy-WSM where it was concluded that the ranking of alternatives was very similar.[141] Moradi et al[138] employed MCDM method for selection of site criteria for wind resource evaluation using ArcGIS for central Iran. The topographical, structural, and environmental criteria and their sub-criteria were applied to eliminate unfavorable locations. The analysis considered the slope of the wind speed, topography, proximity to the electricity grid, substations, urban areas, highway, and roads to find weights using AHP. There were 16 sub-criteria considered in finding weights in order to rank sites for wind farm installation. The study concluded that 80% of the study area was not suitable for wind farm installation. The wind energy potential was concluded to have the highest weight followed by distance from power lines and slope of terrain with least weight. The South-Eastern area of the province, including Karaj and Nazar Abad County, was evaluated to have the highest potential zone of Alborz province.[138] Sahar and Seyed[139] proposed method to choose suitable areas for installation of wind farm-site in Takestan Plain as higher potential site for wind farm in Qazvin Province employing AHP technique. In spite of the natural and artificial barriers to install wind farms in this province, it was estimated that only 1% of the area under consideration could have capacity of 500-MW from wind energy. The proposed model was claimed to have versatility in implementing for other sites in terms supplying appropriate final weights and tolerable fuzzy thresholds by DMs. In addition to that, it takes into account resultant weights derived by experts for resolving conflicts and disagreements. This approach made use of involvement of various stakeholders and experts, individuals, managers, and DMs as well. The selection criteria for site were categorized into primarily three sets of technical, environmental, and geographical with buffer zones around wind farms as limitation and not involved into site selection analysis. It was determined that wind speed was identified as the most sensitive criterion followed by slope and distance from population centers.[139] A case study to identify the most suitable site for wind farm in eastern part of Iran has been attempted by Chamanehpour et al.[146] The analysis was conducted using MCDM in GIS environment with AHP and fuzzy methods to model for suitable site extraction. In the study, 16 layers of information comprising: temperature, slope, wind speed, altitude, villages and towns, primary and alternative routes, airport, protected zones, land utilization, water bodies, earthquake acceleration, and faults were considered as the fundamental decision-making sub-criteria. Based on evaluation, Zirkouh of Ghaen, east of Darmian, Sarbishe, Deyhouk, and north of Khoosf was found suitable for planning wind farm. It was concluded that out of the total study area, 3.3% (equivalent to 4887.7 km^2) in AHP method and 4.5% (equivalent to 6709.3 km^2) in Fuzzy method were located in the excellent region that has an ability to construct wind power plants. Furthermore, the area located in the north-west of Khoosf was suggested as the most promising location for the wind power plant.[146]

Ur Rehman et al[147] proposed an integrated qualitative and quantitative MCDM framework for choosing sites for installation of wind energy power plant for energy industry in a province of gulf country. The method investigated expert-based and entropy-based criterion weight computation and considered five feasible options for wind farm locations with around 15 response criteria for each alternative to evaluate the best possible one. The Saudi Arabia was planning to set up the country's first large-scale wind farm of installed capacity of 400 MW to cater rising demand of electrical energy, which is expected to hit 55 GW by 2020. The 17 criteria were selected based on opinions of experts and literature.[47-49] The economic and environmental factor,[148] social acceptability,[149] power demand,[150] and even uncertain events, like reliability and maintainability issues,[151] were considered as key criteria. In comparison with AHP and ELECTRE, PROMETHEE was selected to figure out decision-making using positive and negative preference. It was deduced that the concepts of preference flow, weights, and geometrical analysis for interactive aid (GAIA) planes, along with sensitivity analyses, made the PROMETHEE methodology more informative for the alternatives ranking. Moreover, it helped DMs to not only prioritizing alternatives but in establishing the superiority of one substitute over another. In order to evaluate site location for wind farm, the criteria considered were average wind speed and average wind power density, power demand, acceptability, environmental impact, form of terrain, geological suitability, expenditure against use of technology, safety threats, tip-speed ratio, security, normal/abnormal instants, accessibility to grid, supply cost, power grid interruption, transportation facility, regional development scheme, and societal concerns.[147]

From the literature survey carried out for site selection of wind farm, mainly economic, technical, environmental, social, and political factors are important aspects for wind-turbine-based power plant development.[152] The key criteria and associated ranks for wind farm location selection if disclosed in literature are depicted in Table 3.

3.4 | Applications of MCDM techniques in load/demand management

Muhsen et al[153] estimated residential electrical load across the world to be approximately 30%-40% of total energy consumption. The routine practice adopted by government is to enhance the generation capacity of conventional generation technology to meet rising demand of electricity, which further leads to the rise in emission of hazardous gases and deep depletion of fossil fuel. In contrast to that renewable-based generation needs higher investment cost and intermittency in extracted power. Demand response is one of the attractive solutions without much additional investment in infrastructural facility but calls for change in consumers' behaviors (ie, change in time or amount of energy demand) through different incentives. The effective load management is supposed to handle costumer load for energy and cost saving. A jump of 5% in consumer's demand is compensated by increasing around 20% additional capacity to ensure sufficient reserve capacity.[154] There are various methods of managing loads like: a robust-index optimization method for unpredictable customer behavior for violation of preferred comfort-level, a weighted-sum multiobjective for residential household applications using time-of-use (ToU) from 2 to 5 time periods, a multi-objective genetic approach for load management for household, a randomize first-order method for large scale of customers, etc. They used the energy cost, incentive offers, and customer's comfort level as objective function and peak load constraint, electricity consumption, sequence of operation for appliances as constraints.

A multiobjective optimization differential evolution (MODE) algorithm was used[153] for load management by curtailing the CoE and comfort level for customer simultaneously, and the options were prioritized from the finest to the worst using MCDM methods. A hybrid AHP and TOPSIS were examined as MCDM methods. The influence of change in time slots on the given optimal solutions was addressed for actual residential load. The proposed method managed indicated energy cost saving of 32%, 44%, and 44% for 10, 5, and 1 minute time slots, respectively, and the peak load savings were 41%, 31%, and 42% for 10, 5, and 1 minute time slots, respectively. The proposed method provided saving in energy cost and peak consumption without exceeding acceptable range of customer inconvenience depicted in Table 4.

The term demand side management (DSM) is used to refer to a set of actions planned to manage optimally a site's energy consumption in order to curtail cost against electrical energy and grid charges including taxes and penalties. Six evaluation criteria, such as compliance flexibility, economic viability, effectiveness, legal feasibility,

TABLE 3 Applications of various MCDM techniques in wind energy–based projects

MCDM technique	Primary attributes	Secondary attributes (rank)	Computed rank
FAHP and FTOPSIS[141]	Agrological capacity	N/A	9
	Slope	N/A	6
	Area	N/A	5
	Distance to airport	N/A	10
	Distance to roads	N/A	7
	Distance to power lines	N/A	4
	Distance to cities	N/A	2
	Distance to electrical substations	N/A	3
	Distance to mast	N/A	8
	Average wind speed	N/A	1
GIS-AHP[138]	Structural	Distance from the supply grid	N/A
		Distance from generating station	N/A
		Distance from substations	N/A
		Distance from gas transmission	N/A
		Distance from railway	N/A
		Distance from highways and roads	N/A
		Distance from airports	N/A
	Topographical	Elevation	N/A
		Slope	N/A
		Faults	N/A
	Ecological	Environmental	N/A
		Protected area	N/A
		Ancient and cultural	N/A
		Monuments	N/A
		Lakes and water bodies	N/A
		River	N/A
		Distance from urban area	N/A
		Distance from rural area	N/A
AHP[139]	Environmental	Wildlife habitat	4
		River	10
		Fault	2
		Urban areas	3
		Rural areas	7
	Technical	Wind speed	1
		Road	6
		Power transmission lines	8
	Geographical	Slope	5
		Elevation	9
GIS-AHP[146]	Geological	Distance from fault	8
		Earthquake acceleration	11
	Environmental	Distance from protected area	6
		Land use	10
		Distance from river	13

TABLE 3 (Continued)

MCDM technique	Primary attributes	Secondary attributes (rank)	Computed rank
		Distance from ground water	15
	Socio-economic	Distance from town	4
		Distance from main route	7
		Distance from village	9
		Distance from secondary route	12
		Distance from airport	14
	Natural	Altitude	2
		Slope	5
	Climate	Wind speed	1
		Temperature	3

TABLE 4 Applications of MCDM in load and demand management system

	Primary attributes	Secondary attributes	Rank
Fuzzy AHP-TOPSIS[155]	Economic criteria	Electricity savings	6
		Pay-back period on DSM investment	10
		Loss aversion related to forced outage	3
		Customer satisfaction	12
		Financing capability power player	15
	Social criteria	Support for development of the energy industry	10
		Electricity savings (C1): measure the red	9
		Contribution toward economic development	5
		Electricity construction investment saving	12
	Environmental criteria	Reduction in greenhouse-gas (GHG) emission	1
		Preventable soil erosion and environmental damage	4
		Conservation of natural resources	2
	Technical criteria	Energy saving transformation of energy consumption devices	7
		Contribution of distributed energy utilization	7
		DSM systems structure	14
AHP- TOPSIS[153]	Cost of energy	N/A	1
	Customer inconvenience	N/A	3
	Peak	N/A	2

political stability, and market revolution capability, have been considered to assess eight various strategies using AHP in Indian context by Vashishtha and Ramachandran.[156] An FAHP-assisted TOPSIS technique was proposed for DSM in commercial sector for China by Dong et al.[155] The experts from diversified backgrounds such as research, government, electricity utilities, and commercial enterprises were involved to collect criteria weights.

As aforementioned, the residential load is accounted as almost one-third of the total electrical demand in the world, and hence, the load management in residential sector has emerged with huge potential. Siksnelyte-Butkiene et al[157] made an extensive review in area of assessment of renewable energy technologies in residential domain. The renewable technologies focused on were: SPV and solar thermal technology, micro-wind technology, heat pumps, and small-scale biomass heating

TABLE 5 Application of MCMD in islanding detection

	Primary attributes	Methods/alternatives	Methods rank
ANP and TOPSIS[110]	Suitability for inverter-based DG	Rate of change of output frequency	4
	Nondetection zone	Phase-jump detection	2
	Implementation cost	Harmonic detection	3
	Feasibility to multiple DG units system	Impedance measurement	1
	Operating hours	Slip-mode frequency shift	6
	Degradation of power quality	Sandia frequency shift	5
	Reliability	N/A	N/A

technology (eg, biomass boilers and pellet stoves). The study carried out was pertaining to mainly three segments, like technology, hybrid energy systems, and energy management. Moreover, the criteria included were economic, social, technological, and environmental for all abovementioned three segments. The economic criterion includes mainly capital investment, total net present value (NPV), and operation and maintenance cost; the most usually focused social criteria were socio-cultural awareness and public acceptance; the most commonly used technological criteria were contribution of renewable sources, operating hours of equipment, and reliability. In order to evaluate the effect on environmental issues of different technologies, the most commonly used were the GHG concentration and environmental impact criteria.[157]

Traditionally, the microgrid functions in grid-interactive mode with the medium voltage network. However, planned or enforced isolation can occur depending on power sharing requirements. Under such abnormalities, it is essential to operate the microgrid autonomously and with stability.[158] An assessment of the need of storage devices and load shedding strategies has been done by Lopes et al.[159] The importance of load management, its methodologies for measuring, prioritizing, and controlling of loads, and impact of active load management on energy storage are discussed by Moran.[160]

There are also a number of factors affecting islanding detection, such as method for energy transformation, connection schemes for DGs, power handling of the DGs, short circuit capacity (SCC) at PCC, and revised norms and regulations. All these constraints and their interactions are unpredictable and cannot be accounted for with deterministic ways. Hence, it is quite challenging to deal with the DMs without expertise. Therefore, the anti-islanding selection for grid-connected solar photovoltaic system (GCSPVS) is investigated suing MCDM method by Datta et al.[110] An ANP integrated TOPSIS method is employed to select the best islanding detection method (IDM) for GCSPVS application. In a decision-making problem, the ANP method handles multiple and mutually dependent features such as goal, criteria, sub-criteria, and alternatives. Applying the proposed MCDM, the prioritization of six IDMs depending on individual aspects in a typical IDM selection for GCSPVS application was conducted (Table 5).

3.5 | Applications of MCDM techniques in energy storage systems

Since, the renewable energy–based generation is stochastic in terms of available power, such as solar, wind, hydro, or tidal; their peak power production and load demand rarely coincide throughout the day and irrespective of seasons even over the year. In such scenario, the optimal management of ESSs has a vital role in maintaining supply–demand and hence in turn a more reliable and flexible grid system. Proliferation of such intermittent renewable-based generation raises the need for higher flexible response, sufficiently large ESS, for battery, compressed air, or flywheel. Integrating and operating the most efficient and sustainable ESS for any project is a big challenge, which involves several stakeholders with quite often different objectives and hence seems impossible to be met by a one technology. The selection of the set of criteria always depends on the objectives and probable technologies. Various MCDM techniques have proven their benefits and effectiveness in either selection of storage technology[161] or capacity sizing.[162] Due to certain limitations of AHP MCDM method and in order to address subjectivity involved, few researchers have integrated fuzzy with AHP.[163-165]

Baumann et al[161] presented an extensive review on MCDM applications for assessment of ESS for grid-connected systems. The well-known four aspects of criteria, like economy, technology, environment, and societal aspects with a large number of associated sub-criteria were focused upon. The combination of these criteria was mainly comprehended using the AHP in combined with other techniques. The weight computation of various criteria was often collected and derived from published research wherein context-free data for expenditure, and impact on environmental were used, resulting in some cases to incompatible comparisons in the analysis. Different energy storage technologies in different domains were overviewed such as electrical schemes (capacitors, super-conducting magnet energy storage [SMES]), electrochemical systems (battery systems such as lithium-ion batteries, vanadium-redox-flow [VRF], batteries and lead-acid batteries), mechanical systems (flywheels, pumped hydro-storage (PHS), compressed air energy-systems (CAES) and adiabatic CAES), thermal systems (in form of sensible and latent storage, chemical heat, etc.), and chemical systems (electricity to chemicals or Power-to-X [P2X] and fuel cells). Various MADM methods, fundamentals, and energy-related applications were summarized taking two aspects into account: criteria for energy-storage assessment, which includes economic, environmental, technical, social criteria, and performance measurement of criteria like methods used and data sources for performance analysis and application area and reference system. A certain viable suggestions for decision-making in the field of ESS were dependent on views of stakeholder involvement, selected criteria and MADM, application cases and associated design of ESS, result presentation, and consideration of unpredicted conditions.[161] Li et al[162] proposed in a new hybrid MCDM method based on Bayesian best-worst method, the entropy weighting technique, and grey cumulative prospect theory in order to determine optimal EES planning considering multiple economic criteria. The Bayesian best-worst method and entropy weighting approach were combined to determine the weightings of criteria, and the grey cumulative prospect theory was incorporated for the performance rankings of different ESS planning programs. It was concluded from the empirical results that a 2 MW LiFePO lithium-ion battery ESS was the ideal choice and even after conducting sensitivity analysis related to different risk preferences of DMs, the choice remained the same. In study return-on-investment (ROI), payback period, net-earning, investment cost, and battery lifetime were reviewed. It was also highlighted that the ROI was more significant than battery lifetime and even was more desirable than payback period. Also, the payback period was given higher priority than battery lifetime and followed by net earnings.[162]

Zhao et al[163] also carried out and extensive assessment for BESS based on fuzzy MCDM techniques and proposed an integrated fuzzy-MCDM model merging Fuzzy-Delphi approach, the best-worst method, and fuzzy-cumulative prospect theory. The broad assessment index system comprised 15 sub-criteria from the economic, technological, performance, environmental, and societal aspects based on Fuzzy-Delphi method. The technology aspect consisted specific energy, specific power, self-discharge rate, cycle life, energy density, and safety (as subjective). Economy included capital intensity, operation cost, ESS profit, and higher profit of grid-interfaced wind turbines. Environment aspect included CO_2 intensity. Energy intensity and energy efficiency were considered as performance criteria while deferral of power grid construction (as subjective) and reduction in system reserve capacity were deemed as sociality criteria. The optimal weights were computed by the best-worst method from the experts' opinions emphasizing the influence of technology adopted and environment risks. The interval values and crisp values are converted to TFN to optimize the use of objective data information using Fuzzy theory, and then the cumulative-prospect theory was used to decide the ranks of various options taking into account risk preferences planners and shareholder. The analysis demonstrated that the Li-ion battery was the most suitable choice for microgrid oriented projects, followed by NaS battery and NiMH battery. Sensitivity analysis showed the impact of risk preferences on alternatives status and concluded that even for various risk preferences of DMs for primary criteria, the Li-ion battery was always preferred over the NaS battery.[163] Tao et al[166] proposed method which can be used to analyze thermal ESS in CSP plants. The various 10 heat storage systems were evaluated with 10 criteria. In their work, the linguistic variables were represented by membership degrees applying the axiomatic fuzzy set theory, then the TOPSIS technique was applied. The various criteria conserved into analysis were capital expense, operating and maintenance costs, electricity production, expenditure against thermal storage, levelized cost of electricity (LCoE), advanced technology, environmental impact and safety, land utilization, and freezing point. They concluded that the use of molten salt helps to reduce the price of electricity and improves the energy performance in an eco-friendly way as salt is comparatively inexpensive and more environmentally gentle than present heat transfer fluids (HTFs), but contradictorily the high freezing point leads to significant operating and maintenance issues and requires an advanced freeze protection system.[166]

A similar analysis was also conducted for energy storage technologies while exploiting benefits in context of power quality using AHP and Fuzzy logic as MCDM techniques by Barin et al.[164] Various energy storage elements considered were pumped hydro storage, CAES, hydrogen storage, flywheel, and super-capacitors. The key objective of analysis was to develop the most appropriate storage energy system. The criteria in analysis were costs, power quality, load management, efficiency, technical maturity, and lifecycle.

4 | DISCUSSION

An exhaustive survey of scientific articles by applications in electrical energy revealed that MCDM techniques are generally employed to deal with issues of selection of technology and project, energy policy and planning, site selection of solar PV and wind farm, and demand or load management. The AHP and ANP are the mostly preferred techniques evaluation of generation technologies, project and generation site selection problems (around 20%-25%). AHP and ANP are the most popular and can be blended with other methods and is comparatively faster method. It suffers from a drawback that the results need verification. Secondly fuzzy sets are used impact analysis assessment of generation technologies (around 15%-20%). It can handle subjective and vague data and combination with TOPSIS or AHP would be preferred by many researchers. TOPSIS is the third acceptable method for policy and technology evaluation around 15%-20%. It has straightforward computation steps and has rational and comprehensible logic and generates consistent and reliable results. It can be easily adapted to address energy sustainability problems. ELECTRE, PROMETHEE, and VIKOR stand at almost equal place energy project planning and policy selection (around 10%-15%). ELECTRE and PROMETHEE are preferred when blending of alternatives is complex, but they can be used when comparing results from various methods to achieve reliability in evaluation. ELECTRE suffers from demerits of helping priorities of alternatives but not highlighting difference magnitude between alternatives. Although, both PROMETHEE and ELECTRE have comparatively higher computation requirements.

5 | CONCLUSIONS

This article discusses different MCDM methods together with their applications in energy-related areas. An exhaustive study was carried out exploiting almost every crucial energy applications ranging from the integration of RESs into the existing power systems to planning of new electrical facilities (eg, sitting and sizing of solar PV and wind farms) and policy framing for them. Looking at the significance of energy storage elements in order to manage intermittent nature of RES, the applications of optimal sizing or selection of the best technologies were also studied carefully. It was observed that AHP and TOPSIS assisted with fuzzy integration has been the first choice to handle uncertainties and subjectivity of problem but, the other methods, such as ELECTRE, BWM, BOCR, VIKOR, and PROMETHEE have carved their niche by researchers depending on demands and requirements of project applications. Identification of attractive sites for either solar or wind farm construction was mainly assisted by GIS with MCDM technique. Furthermore, the applications of MCDM methods in load or demand management in residential or commercial sector were also explored. Though, there are many area remained shallow explored, like selection and placement of energy storage devices, prioritizing energy management in energy intensive industries, optimum placement of reactive power management devices, route election for transmission lines, etc. The MCDM techniques have extended its applications from selection of candidates for a firm to site selection for hotel in tourism management, raw material management to prioritizing of processes in manufacturing industries, and selection of the best product in consumer and marketing field; but these methods suffers from certain drawbacks; one and most crucial is the priority changes dramatically when assignment of weights are not done carefully for qualitative parameters or experts involved do not have required skill and expertise. Though, variation in ranking will not get affect severely for quantitative factors having realistic values. This study definitely furnishes rich and multifaceted information of applications of suitable MCDM technique to researchers and decision-/policy-makers in the field of electrical energy inclined applications found unexploited at all or superficially applied.

ORCID

Shabbir S. Bohra https://orcid.org/0000-0001-9209-9412

Amjad Anvari-Moghaddam https://orcid.org/0000-0002-5505-3252

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