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REVIEW ARTICLE **RENREABLE ENERGY**

Decision-Support Frameworks in Renewable Energy Planning: Comparative Insights and the Central Role of AHP

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ABSTRACT

The growing need for rapid decarbonization has greatly increased the complexity of renewable energy planning, which requires multi-criteria decision-making (MCDM) frameworks to balance multiple, and sometimes conflicting, decision objectives. Among the various MCDM techniques, the analytic hierarchy process (AHP) is one of the most widely used methods because of its capability to break down complex problems into hierarchical systems and to combine quantifiable information with qualitative judgments from experts. This paper synthesizes the literature related to the application of MCDM in renewable energy planning, specifically focusing on AHP's applications to technology selection and prioritization, site selection and infrastructure placement, and policy development. This paper compares and contrasts AHP with other MCDM families, identifies hybrids and new methodologies (including spatial analysis, uncertainty models, and participatory governance), and assesses current trends in MCDM research. Additionally, this paper uses examples from around the world to discuss some of the long-standing methodological challenges associated with using MCDM for renewable energy planning (expertise bias, rank reversal, and scale sensitivity), and offers suggestions to improve the rigor and transparency of MCDM use in renewable energy planning. Finally, this it argues that AHP and its hybridized versions can be critical components to achieve alignment between decision processes and the tenets of energy justice and the broad objectives of international sustainability frameworks (net-zero and climate resilience targets).

أطر اتخاذ القرار الداعمة لتخطيط نظم الطاقات المتجددة: دراسة مقارنة و إبراز الدور المركزي لأسلوب التحليل الهرمي للعمليات

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الكلمات المفتاحية

أسلوب التحليل الهرمي للعمليات
نماذج القرار الهجينة
اتخاذ القرار متعدد المعايير
تخطيط الطاقة المتجددة
التحولات المستدامة في قطاع الطاقة

الملخص

أدّت الحاجة المتزايدة إلى تحقيق إزالة الكربون بصورة سريعة إلى زيادة كبيرة في تعقيد عمليات تخطيط الطاقة المتجددة، الأمر الذي يتطلب اعتماد أطر متعددة المعايير (MCDM) لاتخاذ القرار بهدف تحقيق التوازن بين مجموعة من الأهداف القرارية المتعددة، والتي قد تكون متعارضة في بعض الأحيان. ومن بين مختلف تقنيات اتخاذ القرار متعدد المعايير، يُعد أسلوب التحليل الهرمي للعمليات أحد أكثر الأساليب استخدامًا على نطاق واسع، نظرًا لقدرته على تفكيك المشكلات المعقدة إلى أنظمة هرمية مترابطة، ودمج المعلومات القابلة للقياس الكمي مع الأحكام النوعية المستندة إلى خبرات المتخصصين. تستعرض هذه الورقة الأدبيات العلمية المرتبطة بتطبيق أساليب اتخاذ القرار متعدد المعايير في مجال تخطيط الطاقة المتجددة، مع التركيز بصورة خاصة على تطبيقات AHP في مجالات اختيار التقنيات وترتيب أولوياتها، واختيار المواقع وتحديد مواقع البنية التحتية، إضافةً إلى تطوير السياسات. كما تقدم الورقة مقارنة تحليلية بين AHP وعائلات أخرى من أساليب اتخاذ القرار متعدد المعايير، وتحدد المنهجيات الهجينة والأساليب الحديثة الناشئة، بما في ذلك التحليل المكاني، ونماذج عدم اليقين، وآليات الحوكمة التشاركية، مع تقييم الاتجاهات الحالية في أبحاث (MCDM). علاوةً على ذلك، تستعرض هذه الورقة أمثلة عالمية لمناقشة بعض التحديات المنهجية المستمرة المرتبطة باستخدام أساليب اتخاذ القرار متعدد المعايير في تخطيط الطاقة المتجددة، مثل انحياز الخبراء، وانعكاس الترتيب، وحساسية المقاييس، كما

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تقدم مقترحات لتعزيز الصرامة العلمية والشفافية في تطبيق منهجيات MCDM ضمن عمليات تخطيط الطاقة المتجددة. وأخيرًا، تؤكد الورقة أن أسلوب التحليل الهرمي للعمليات (AHP) ونسخه الهجينة يمكن أن تمثل مكونات أساسية لتحقيق المواءمة بين عمليات صنع القرار ومبادئ العدالة الطاقية والأهداف الأوسع لأطر الاستدامة الدولية، بما في ذلك تحقيق أهداف الحياد الكربوني وتعزيز المرونة المناخية.

Introduction

Global growth in renewable energy is greatly increasing the complexity involved with how energy decisions are made today. Renewable energy planners, policy makers, regulators, investors, and community members all have to make difficult choices about renewable energy based on a multitude of technical, economic, environmental, and social issues [1–3]. These types of challenges have caused multiple approaches to assist planners in analyzing different factors that impact their decision making processes using transparent, logical, and sustainable analytic tools. MCDM (Multi Criteria Decision Making) methodologies and especially AHP (Analytical Hierarchy Process), have been widely used as an analytical tool for renewable energy planners around the world [4–8].

AHP's large-scale use is due in part to many facets that include breaking down complex decisions into hierarchical elements, providing a structured method of comparing all elements based on a hierarchical level by using pairwise comparisons, and incorporating both qualitative, subjective, and quantitative information into one decision-making process. Reviews of the literature have shown that AHP is used in nearly all types of energy systems planning and that it is commonly integrated into hybrid multi-criteria decision support methodologies [9–11]. In addition, recent studies have also developed AHP based methodologies using additional techniques such as distance-to-ideal solutions, spatial analysis, and uncertainty modeling to provide more realistic and robust decision results [12– 15].

MCDM analyses offer an effective way to resolve these trade-offs. A wide variety of MCDM models have been used to provide this balance between competing priorities [16 -18]. In addition to providing useful analytical techniques to facilitate decision making, MCDM also provides an approach to collaborative or participatory decision making to assist the transition to new energy systems, and to assist in ensuring that decision-support tools reflect equity orientated policy objectives [19 – 22].

The AHP is, by far, the most commonly used Multi-Criteria Decision Making (MCDM) method, in the field of Renewable Energy Planning over the last decade. The scope of AHP application in Renewable Energy Planning covers the evaluation of different technologies for Renewable Energy Generation, the selection of the best locations for Renewable Energy Projects, the Assessment of Environmental Impacts of Renewable Energy Technologies and the Development of National and Local Policies on Renewable Energy [23, 24]. One of the key differences of AHP compared to other multi-criteria analysis methods is the ability to be used by both technical and non-technical individuals, which facilitates inclusive and Participative decision making, which are consistent with the democratic values underlying Sustainable Energy Transitions.

Although MCDM methods, including AHP, have made significant contributions to the planning of renewable energy, there are multiple important areas of future research necessary to allow for the full potential of these methodologies to be realized. A frequent limitation of present studies of renewable energy using MCDM is that they are generally localized; therefore, although these studies can provide substantial insights into the applicability of an MCDM approach in a particular context, they generally limit the generality of their results, and prevent the formulation of broader frameworks for decision making that could be applicable across various geographic areas or political settings. The need for additional refinement of methodology is also apparent to account for the continued problems of uncertainty in the use of data, and the presence of bias in the process of expert elicitation. Although the use of fuzzy logic and hybrid models have been added to improve upon traditional approaches, additional rigorous testing will be required to ensure that these new approaches produce outcomes that are reliable and reproducible, and that the subjectivity associated with larger-scale decision problems is minimized.

There exists a major conceptual disconnect between social, political, and equity based factors and their representation within current models. Most current models are primarily technocentric and do not sufficiently represent critical components such as: Community Acceptance; Energy Justice; Socio-political Legitimacy. Therefore future research must be directed toward bridging this gap and developing a broader scope of models which provide a holistic understanding of energy transitions beyond solely economic and technical indicators. Further, the proliferation of Hybrid MCDM Models indicates a parallel need for Standardized Evaluation Metrics to enable comparison of the effectiveness of different Hybrid configurations across different technological, geographic contexts and most importantly under Climate Uncertainty Conditions to identify Optimal Approaches.

Therefore, all subsequent research needs to be focused on an empirical approach to develop valid frameworks which will enable planners of renewable energy to successfully consider and weigh the multiple technical, economic, environmental, and social political criteria associated with renewable energy planning. The development of additional methodologies to further limit or reduce the influence of the subjective opinions (expert) and uncertainties in the group decision-making process, and the creation of robust assessment protocols to evaluate hybrid models and their performance in various locations are two important directions for future research. Finally, it is essential to develop the application of MCDM methods to international sustainability objectives, including the Paris Agreement and the UN's Sustainable Development Goals, to increase the adoption of these methods by governments and other organizations to achieve long-term and sustained changes in energy use through sustainable energy transitions.

In this respect, the purpose of the current study is to provide an integrated overview of the application of MCDM methods for energy planning, with a focus on AHP. It also seeks to demonstrate the potential policy-oriented and practical uses of AHP through integration of the results of both empirical/analytical studies and a bibliometric analysis of existing literature and emerging methodological developments, while demonstrating the importance of

MCDM frameworks as tools for policy development for the achievement of a sustainable pathway to achieve a net-zero transition.

Data and Methods

Using an international focus on technology selection, site selection and policy development; the study assesses how MCDM methodologies are able to provide guidance for varying planning strategies. This study will use both qualitative methods and quantitative methods to develop an overall decision support methodology that includes a combination of empirical data and expert opinions, which enhances the ability of planners and policymakers to make decisions regarding the many complex aspects of energy transition. Additionally, the research illustrates AHP's significant contributions to this area and demonstrates how AHP can be combined with other MCDM methodologies to resolve the various challenges associated with renewable energy systems.

This research utilizes a variety of high-quality data sources. This includes peer-reviewed journal articles, bibliometric analysis; empirical (case) studies; and the most current (established) models for planning energy, published between 2018 and 2025. Together, these have provided an extremely robust evidence base for the research, documenting recent developments in methodology; current debates in policy; and practical applications of the data for renewable energy decision making. Primary data was obtained from publicly available databases such as those of the International Energy Agency (IEA) and World Bank, as well as various National Energy Agencies, and provided valuable insight into factors such as energy demand, resource supply, cost, and environmental impacts associated with each technology. Secondary data, comprising Expert Opinion and Local Surveys, were gathered to assist with the qualitative aspect of the analysis and are required when using AHP due to the importance of the input from experts in determining the weights assigned to criteria and making comparative evaluations of each criterion.

In addition to providing a wide range of examples from renewable energy planning applications around the world, including those in Europe, Asia and North America, this paper includes specific case studies that demonstrate how AHP can be applied across a variety of scales (from large scale, regional and national level infrastructure projects through to small scale, community-level and/or decentralized systems). The included case studies also provided an opportunity for readers to see how geospatially-based data are being utilized to evaluate potential sites for solar, wind, and biomass energy installations. This is particularly important. As determining the optimal locations of these types of renewable energy installations is heavily dependent upon evaluating a number of factors related to land use, available resources, environmental limitations, as well as other site-specific conditions.

MCDM in the era of renewable energy

A large-scale transformation of global energy systems is complicated task. As numerous challenges need to be addressed simultaneously [25-88]. Therefore, it is necessary to evaluate competing priorities for the technologies that support each country's objectives, identify where these technologies can be deployed most effectively, create paths forward for implementing those technologies, and formulate policies that promote their long term sustainable development [89-92]. Examples of such conflicting issues include the rapidly increasing demand for solar photovoltaic (PV) technology, which is now causing increased pressure on available agricultural land; and therefore, requires an objective evaluation of PV technology based upon land use considerations, economic viability, and societal acceptability [27–29]. Another example includes the growth of offshore wind farms throughout Europe, which have caused the conflict of spatial issues with other marine activities that have been in place for years such as shipping lanes, commercial fishing areas, and marine protected areas [1].

Energy planning issues require a multi-dimensional decision-making framework to accommodate the complexities presented by traditional financial models. In this context, Mardani et al. [6] suggested that, to be able to integrate an array of factors, including economic, environmental, social, and technical considerations, the frameworks need to be able to evaluate all options more holistically. This is possible due to the fact that multidimensional frameworks can capture interaction between different evaluation criteria, account for priorities from stakeholders, and facilitate planning with uncertainty [93–96]. The use of MCDM methods has become an essential tool for addressing these issues [93, 94, 96]. It is important to realize that MCDM Methods are not one size fits all and can be categorized into many different families with varying levels of theoretical basis, advantages, and disadvantages. The ability to categorize MCDM Methods allows researchers and policymakers to design a decision-making model that will specifically meet the needs of the renewable energy project being planned [97–108]. In addition to providing a methodological landscape for research, Table 1 outlines and compares the primary categories of MCDM Methods, including their underlying concepts and typical applications in renewable energy projects.

The outranking methods (such as ELECTRE and PROMETHEE) have advantages in site selection due to their ability to deal with conflicting criteria, non-comparable levels of partial comparison between options, veto thresholds, and non-compensatory decision-making logic [109, 110]. Outranking methods can also provide the decision-maker with an image of the planning reality that is closer to what he really experiences when he has to make decisions on solar, wind, biomass, and offshore energy sites. The decision maker could reject a site, for instance, with good resources if the site does not fulfill some environmental, social, land use, or access to the grid constraints. As such, the outranking methods could provide the planner with a more realistic view of his own constraints than other types of models [14, 111].

Global applications of MCDM in renewable energy policy and planning

MCDM approaches enable planners, policymakers, and stakeholders to consider systematically competing options; incorporate site-specific restrictions on each alternative; and balance multiple goals. Moreover, they allow for the consideration of different geographical, socio-economic, and technological characteristics simultaneously, which provides the basis for making more open and rational choices. From offshore wind farm planning in Europe, especially Germany and Denmark, planning at the interface between energy potential and essential maritime spatial planning needs [1], to wider applications of GIS-MCDM integration for solar and wind siting in China, encompassing siting for technical potential, current land cover and risk to the environment [14]. At the heart of the evolution of MCDM as suitable for widespread application is their ability to incorporate both

Table 1: Classification of MCDM Families and Their Relevance to Renewable Energy Decision-Making

Family Type	Representative Methods	Strengths in Energy Planning	Limitations	Illustrative Applications	Reference
Value Measurement	AHP, ANP, SMART	Transparent hierarchy structuring; allows both qualitative and quantitative criteria; consistency check possible	Subjectivity in pairwise judgments; scale sensitivity	Prioritizing solar vs. wind investments in Turkey; biomass technology evaluation in Lithuania	[5, 24, 101]
Outranking	ELECTRE, PROMETHEE	Good for handling conflicts; can deal with non-compensatory criteria	Requires strong data; complex for non-experts	Renewable policy selection in Greece	[9, 102]
Distance-Based	TOPSIS, VIKOR	Computationally efficient; intuitive “closeness to ideal” concept	Sensitive to normalization method; ignores preference uncertainty	Site selection for solar parks in China	[10, 14, 103]
Recent/Hybrid	BWM, Fuzzy MCDM, AI-integrated models	Robust in handling uncertainty; less sensitivity to rank reversal	High complexity; difficult for stakeholder engagement	Fuzzy–AHP for wind energy in India hybrid AI–AHP for smart grids	[104 – 108]

quantitative drivers and qualitative values, the transparency of providing structure to decisions and clarity of the trade-offs required, as illustrated in Fig. 1.

The use of these methods in the energy literature needs to be quantitatively reviewed to validate theoretical differences between the families of MCDM in real-world applications. Because it is unlikely there will be a database that can accurately classify each method within a particular energy application, a meta-synthesis has been completed to identify and synthesize the results of recent, high-quality, bibliometric reviews and scoping studies on energy applications to provide robust estimates of method usage rather than precise data. Overall, AHP and TOPSIS have the most practical application to energy systems, as evidenced by the overall use of these methods in energy system applications; additionally, an examination of the largest bibliometric synthesis indicates that AHP provides the weights, while a ranking method is used to make decisions [10, 14, 112].

Because the suitability of MCDM methods varies across different renewable energy planning tasks, Fig. 2 compares the relative applicability of major approaches across technology selection, site selection, policy design, storage planning, microgrids, and hybrid systems. This comparison emphasizes that method selection should be aligned with the specific structure, objectives, and complexity of the decision problem.

An assessment of 134 Web of Science-indexed research articles concerning clean energy systems between 2018 and 2021 was conducted using bibliometrics [10]. The results indicated that there is a strong hierarchical structure when it comes to methodology usage in this area of study: nearly 80 percent of all methodologies were one of four methodologies, with AHP being used most frequently (38%), followed by TOPSIS (24.8%), then VIKOR (12.8%), and lastly, ANP (11.2%) (See *Fig. 3*). The use of AHP and TOPSIS as a combination represented the majority of the methods used in clean energy systems, while the combination of VIKOR and ANP made a considerable portion of the remaining quarter. These findings are consistent with prior comprehensive review literature, which identified similar levels of usage of AHP and TOPSIS in decision making for renewable energy [3, 6].

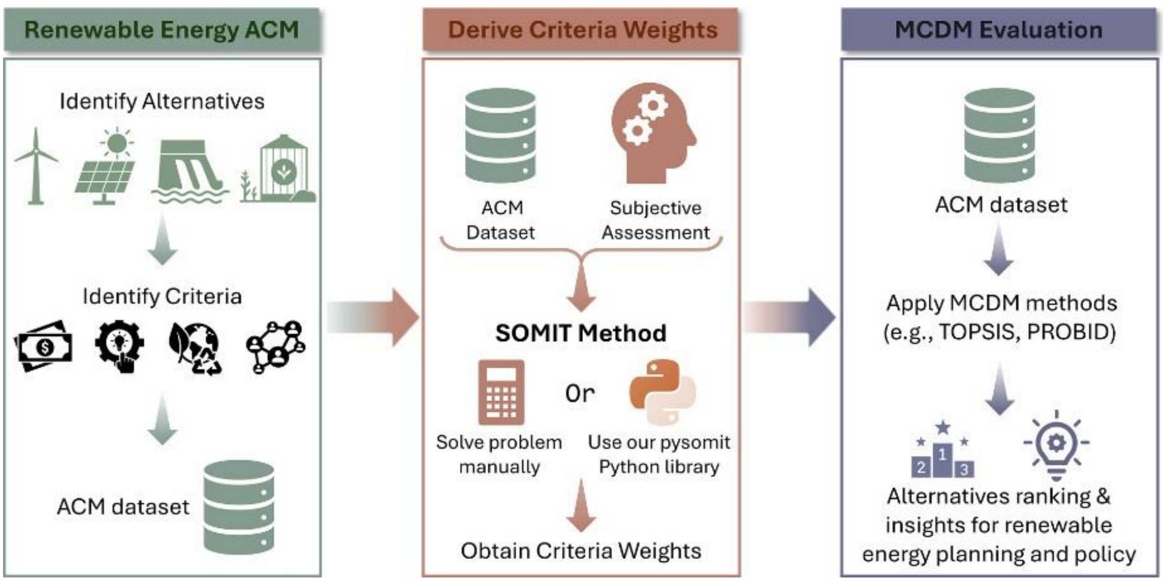

Figure 1: Decision-Making Process in Renewable Energy Planning Using MCDM

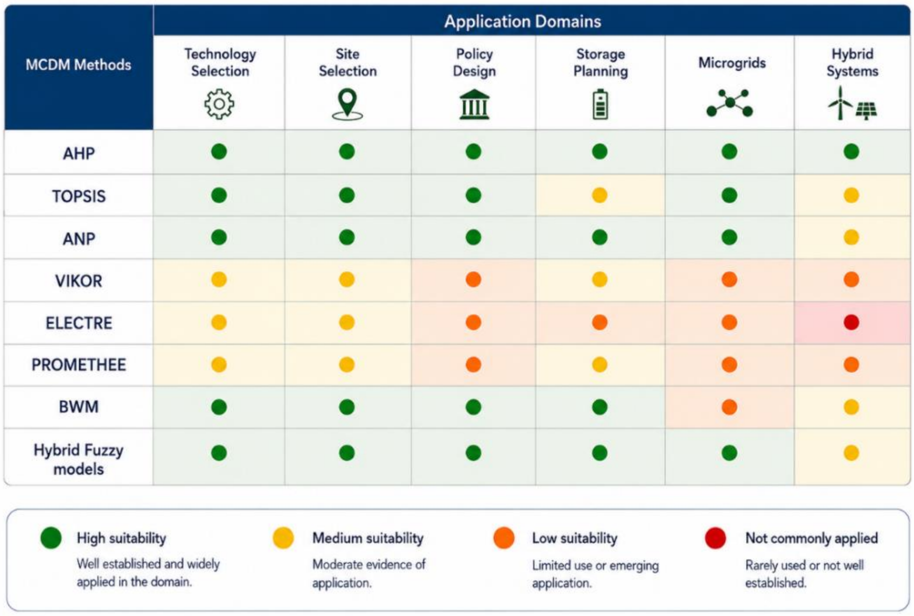

Figure 2: Method–application mapping of established MCDM techniques for renewable energy planning

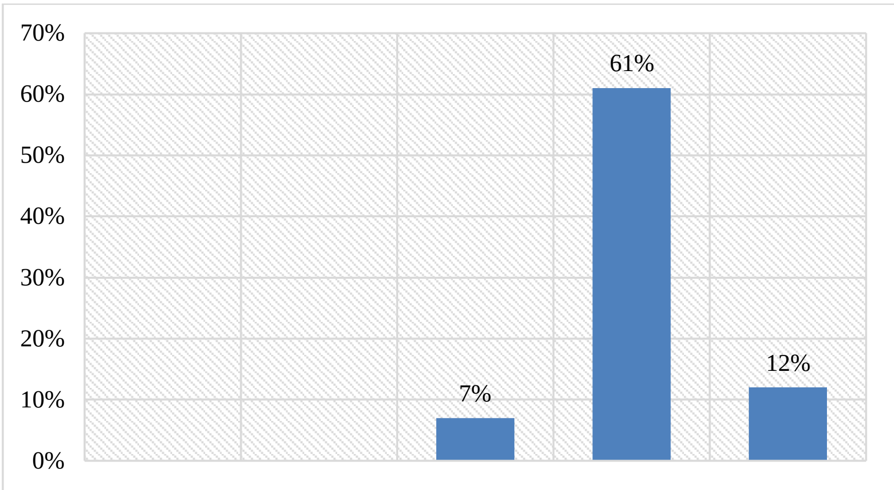

Figure 3: Method shares in clean energy systems MCDM studies (2018 - 2021)

Additional evidence supporting the use of multiple methods is found through the many different energy-related synthesis reports. An 85-paper review article on site selection methodologies published in Renewable Energy between 2001 and 2018 reported that AHP and TOPSIS were by far the most frequently used methodologies, and ELECTRE and VIKOR were the two next most commonly used methodologies [14]. Similarly, a general review of methodologies for selecting clean energy options under conditions of uncertainty (between 2018 and 2021) describes a trend in which AHP was frequently employed to determine weights among criteria, followed by application of a measure of distance to an ideal condition (for example, using TOPSIS to rank alternatives) [10]. Further reinforcement of this trend can be seen in broader bibliometric studies of methodologies and applications in environmental and energy engineering during the 2010s and 2024, where AHP, TOPSIS, VIKOR, PROMETHEE, and ELECTRE have been identified as one of the primary methodological clusters [11].

AHP's frequent use as a weight/structure layer in the structure of energy MCDM pipelines can be further contextualized through its global application; over 29,000 publications that were tagged for AHP globally between 2012-2022, with over 10,000 of them directly connected to the United Nations' Sustainable Development Goals; AHP has been used on a global basis within many domains that are oriented toward sustainable development, including the energy domain [113].

The analysis of bibliographic data from 2015 through 2025 provides a well-defined, evidence-based viewpoint about how the landscape of Multi-Criteria Decision-Making methods has evolved during the last ten years within the context of clean energy planning. The AHP has been used as the core "base" decision-making tool as an anchor method for the development of criteria and weights prior to coupling it with another decision-making methodology to determine rankings [114]. The consistent presence of AHP as a top-ranked methodology throughout the past decade is supported by its prevalence (about 30%) in the clean-energy bibliometrics that report explicit counts (2018-2021), which is also reflected in earlier seminal reviews [115] and later reviews of energy-related applications [14, 116, 117]. AHP has been complemented by TOPSIS as the primary "ranking" method, accounting for approximately 25% of clean-energy publications (2018-2021), and is also the most frequently coupled hybrid AHP framework, due to its ease of interpretation and its robustness against sensitivity behaviors [10].

On the other hand, Vikor and ANP show a significant "Second Tier" of use together, and represent a considerable portion of the overall usage. Vikor is used at about 13% for its ability to determine what is called "compromise" solutions, which can be beneficial if there is an emphasis on weighing competing and potentially conflicting objectives, and/or when the penalty of extremes may be necessary, especially in policy and infrastructure siting applications [118]. The use of ANP at about 11% represents applications in which relationships between the interdependent and mutually influential criteria are important, and where network dependency modeling would be important for detailed studies of the nuances of energy planning [10]. While outranking techniques such as PROMETHEE and ELECTRE have less of a presence in purely clean-energy corpora, they have a continued but somewhat niche presence. This is primarily due to their applicability to those studies involving strict veto or threshold logic, such as site selection and technology portfolio analyses, as demonstrated by numerous bibliometric studies and reviews [11].

There has been a major increase in hybrid MCDM models since 2020 (especially after), which are represented by the combinations AHP – TOPSIS, AHP – VIKOR, BWM – TOPSIS, and Fuzzy AHP/ANP; and also by the increasing use of GIS-MCDM layers, which reflect the needs of an increased spatiality in decision making and an increased need for transparency/explainability of the decisions [11]. The mentioned methodological approaches, areas of application, and results are then grouped and summarized in Table 2 and used to provide a framework of current trends in research.

While useful, quantifiable results must be analyzed within the framework of how numbers generated from bibliometrics may differ based on the parameters of the specific studies. Those include the scope of the subject matter of the given study (clean energy vs. broader energy and/or environmental energy engineering), used databases (Web of Science, Scopus, and Dimensions), and defined coding (primary methods vs. secondary methods). While source-specific numbers are useful indicators of trends, they are typically confirmatory directionally speaking as opposed to replicating numbers precisely. Practitioners of planning and/or policy commissions have empirical evidence supporting AHP as a starting point for those interested in MCDM, with TOPSIS being a natural pairing for straightforward interpretation [121]. ANP should be considered when there are significant interactions among the criteria [122]. VIKOR has been widely accepted as a viable option when a compromised solution is desired, as it relates to conflict resolution [123]. However, when an individual or group requires a hard veto threshold to define their evaluation process, or requires semantic definitions of outranking, PROMETHEE and ELECTRE will continue to be preferred options [124].

The centrality of AHP in Renewable Energy Planning

AHP was developed by Thomas Saaty in the latter part of the 1970s, and it has evolved into the premier method for multiple objective decision analysis due to its ability to reduce complex decision-making problems into a hierarchical model of objectives, attributes, sub-attributes, and alternatives [6]. Essentially, the mechanism that makes AHP work is based upon the pairwise comparison of each element at each level of the hierarchy using a standard scale of relative importance; with each judgment being converted into a priority vector after normalization; and finally, an evaluation of consistency is performed to validate both the reliability and logic of the decision-maker's inputs [125].

An important strength of AHP, especially in the challenging domain of public policy and infrastructure planning, is that it allows for the integration of the expertise of decision makers with the preferences of stakeholders and with many times non-quantifiable “soft variables”, such as social acceptability, environmental justice and political feasibility, that are very hard to be quantified or monetized using traditional methods [126]. This is an important asset when working in the highly competitive area of renewable energy planning because all decisions require balancing competing trade-offs among

Table 2: Representative bibliometric/systematic reviews of MCDM in renewable energy planning (2015–2025)

Study	Bibliometric Window	Sample Size (n)	Dominant Methods Assessed	Key Insights
[6]	1995–2014	505 articles	AHP, TOPSIS, ELECTRE, VIKOR	Early comprehensive synthesis; highlighted AHP as the most widely applied, with emerging hybridization trends.
[24]	2000–2017	90+ studies	AHP, TOPSIS, PROMETHEE	Focused on renewable energy investments; emphasized methodological flexibility and geographic heterogeneity.
[16]	2000–2018	150+ papers	Symmetry-focused decision models incl. AHP/ANP	Identified increasing complexity in hybrid MCDM structures.
[8]	2005–2019	198 papers	AHP, Fuzzy-AHP, TOPSIS	Documented the expansion of fuzzy hybridization to handle uncertainty in renewables planning.
[117]	2010–2020	125 studies	PROMETHEE, ELECTRE, AHP	Found a rising role for outranking methods in power system resilience and sustainability assessments.
[10]	2010–2021	500+ Scopus-indexed studies	AHP, TOPSIS, VIKOR, ANP	Provided quantitative shares; confirmed AHP’s dominance but growth of TOPSIS and hybrids.
[107]	2010–2021	210 studies	AHP, fuzzy methods, hybrid models	Highlighted transition from classical AHP to fuzzy–GIS integrated frameworks.
[23]	2012–2023	320 articles	Hybrid MCDM (AHP-TOPSIS, AHP-VIKOR)	Identified an exponential rise in integrated MCDM for large-scale renewables projects.
[119]	2015–2024	400+ articles	DEA, AHP, TOPSIS	Noted increasing convergence of MCDM with efficiency analysis (DEA) and AI-based models.
[120]	2016–2025	240 articles	AHP, ANP, fuzzy hybrids	Illustrated robust growth of ANP as a network-based alternative to AHP in urban sustainability and renewables.

various dimensions, including economic viability, technical feasibility, environmental sustainability, and social-political acceptability [127]. When looking at the different types of energy systems available like wind, solar, biomass, and hydroelectric power, AHP can be used by planners to make a careful assessment of the costs and benefits associated with each type of system in addition to the more tangible factors such as the levelized cost of the energy produced, but also the softer factors such as land availability, the greenhouse gases that could be reduced and the ability of a particular community to support the construction of a facility and/or to use the product generated [128].

The use of AHP has also continued to be advanced by the continuous improvement of its methodological strength, especially through recent developments in the use of fuzzy logic to address the imprecision inherent in human judgment [129], through the use of GIS-AHP hybrids that assist in spatial decision making to identify the best locations for renewable energy infrastructure [130] and through the increasing application of AHP-DEA combinations which integrate AHP as an input to structured evaluation with DEA as a method for measuring efficiencies in areas such as energy efficiency benchmarking [131, 132]. These strategic improvements have greatly expanded the scope of AHP's applicability, moving it beyond a simple ranking tool to become an effective means of strategic system planning – particularly under conditions of uncertainty. Table 3 presents a comparative review of several examples of case study work, illustrating how AHP has been employed in different geographically located and technologically oriented applications to assess alternative energy options, to prioritize investments, and to guide strategic policy decisions made at the local, regional, and national levels.

Despite its widespread use in renewable energy applications, the suitability of the AHP depends significantly on various factors. The types and number of criteria considered, the reliability of available data, the uncertainty, and the societal and institutional constraints are all factors that affect the outcome of the decision-making process [3, 6, 133]. In this context, to ensure that the results from AHP studies are appropriately applicable to different contexts, they have to undergo an appropriate level of sensitivity analysis and robustness testing.

Therefore, it is important to see AHP as part of a broader MCDM framework with multiple components, which can help to structure decisions concerning renewable energy in a way that takes into account the various aspects of individual problems. However, in certain applications, other alternative methods may have an advantage over AHP. As an example, TOPSIS and VIKOR are more applicable to distance-to-ideal and compromise-ranking problems. Other alternatives, such as ANP, are best suited when there are strong interdependencies among the decision factors. On the other hand, PROMETHEE and ELECTRE offer advantages for non-compensatory thinking, veto limits, or strict outranking logic rules are required for decision-making [14, 24].

To position AHP within the broader renewable energy decision- support landscape, Figure 4 illustrates its connections with major complementary methods, including GIS, AI/ML, fuzzy logic, DEA, ANP, TOPSIS, VIKOR, ELECTRE, PROMETHEE, and BWM. It also highlights the integrative role of AHP as a core framework that can be combined with spatial, computational, and multicriteria techniques.

Despite being widely accepted and utilized to demonstrate great utility in numerous renewable energy-related applications, the AHP is still under extensive methodological review. There is continued scholarly debate about many

Table 3: Comparative Global Applications of AHP in Renewable Energy Planning (2015–2025)

Country/Region	Energy Type / Focus	Application of AHP	Key Outcomes / Insights	Reference
India	Biomass, solar, wind	Prioritization of rural electrification technologies	Biomass ranked highly due to job creation and resource availability; solar chosen for long-term sustainability	[3, 10]
Turkey	Wind, solar	National-level renewable portfolio prioritization	Hybrid solar–wind systems identified as optimal for energy security and carbon reduction	[5]
Lithuania (EU)	Policy instruments (tariffs, subsidies, taxes)	Policy prioritization using AHP with stakeholder input	Feed-in tariffs ranked highest; carbon tax lowest due to political resistance	[24]
China (Chengdu)	Solar PV siting (urban & peri-urban)	GIS-integrated AHP for land-use conflict analysis	Identified optimal PV zones minimizing conflicts with agriculture & urban expansion	[107]
Bangladesh	Off-grid solar programs	Rural development and electrification strategy	Off-grid PV prioritized over grid extension for rural energy access	[3]
Brazil	Biomass energy	Evaluation of bioenergy projects	Biomass ranked as most sustainable pathway for both energy and agricultural synergies	[117]
Germany	Wind and solar policy	AHP applied for policy instrument evaluation	Investment subsidies more acceptable than feed-in tariffs due to EU market integration	[16]
United States (Chicago)	Solar PV deployment	Multi-stakeholder planning framework	Rooftop PV favored over large solar farms due to socio-political acceptance	[5]
North Africa (Libya, Morocco, Egypt)	Large-scale solar	Siting of solar mega-projects with AHP-GIS	Optimal sites balance irradiation potential with socio-political stability and water use	[130]
Bangladesh & Nepal	Hydropower	AHP for prioritization of hydropower investments	Medium-scale hydropower ranked above mega-dams due to social displacement concerns	[18]
Saudi Arabia	Green hydrogen	AHP for energy carrier selection	Hydrogen ranked above natural gas and solar thermal for export potential	[23]
Global (multi-country studies)	Policy and investment	Comparative energy planning using hybrid AHP models	Cross-country benchmarking highlights AHP as a flexible policy assessment tool	[1, 119]

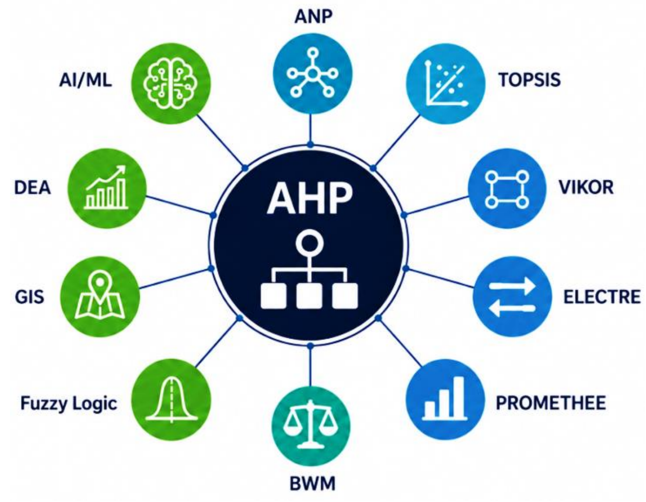

Figure 4: The central role of AHP in renewable energy planning

facets of this approach (despite its recognized advantages of providing clarity, transparency, and a logical decision framework). However, there are still many debates among scholars regarding the AHP methodology. One of the main criticisms of the AHP methodology involves the possibility of rank reversal. This happens when the ranking of alternatives changes by adding to or removing a criterion from the decision set. Yet, this has been interpreted as a reflection of the context-dependent nature of real-world decision-making [16].

Furthermore, due to its inherent reliance on subjective expert-based pairwise comparison decisions, AHP is highly susceptible to the limitations of subjectivity as well as possible bias in the decision-making process [134]. An example of this would be when experts unintentionally weigh disproportionately higher or lower importance for specific criteria that they use to determine their comparative preferences, which will ultimately influence the ranking of the options [6, 8]. In a multi-stakeholder energy planning context, where there are multiple stakeholders providing input into the decision-making process, these different perspectives of the various stakeholders could significantly affect the outcome of the decision [135]. However, fuzzy extensions of AHP have been developed to help reduce or eliminate the potential for biased judgments by modeling the uncertainty of these judgments and reducing the cognitive biases that occur when making judgments [107]. There continues to be debate about how the scaling and ratios used in Saaty's 1–9 scale create an artificial linearity in what could otherwise be non-linear judgments, thereby creating distortions, particularly in larger hierarchical decision-making contexts [115]. As a result, there has been increasing advocacy for hybrid approaches using entropy weighting or statistical normalization to counteract the negative scaling effects [23].

Although fuzzy logic could potentially mitigate some of the inherent limitations of the AHP process (experts' subjectivity), the effectiveness of this approach has yet to be empirically demonstrated. Fuzzy AHP provides a means of reducing the rigidity associated with making precise pairwise comparisons using fuzzy numbers to represent the linguistic nature of uncertainty; it will not remove either subjective judgment from experts or group decision-making bias [136]. In addition, while hybrid models such as AHP-TOPSIS, AHP-VIKOR, Entropy-AHP, and Grey-AHP provide an improved level of analytical robustness relative to other methods that combine different functionalities, their ability to perform well will depend on the stability, replicability, and interpretability of their results when model assumptions change [14, 133]. Thus, future AHP-based renewable energy studies will need to assess the effectiveness of corrective strategies that include consistency ratio assessment, sensitivity analysis of weighting of criteria, rank reversal testing, cross-method evaluation of preference structures, and uncertainty propagation using fuzzy, grey, probabilistic, and Monte Carlo-based techniques. Specifically, sensitivity analysis may help identify if the ranking was overly reliant upon the weight assigned by a subjectively biased expert. Cross-method validation may provide an answer as to whether the same options would continue to receive a higher ranking than others using different families of MCDM methodologies, i.e., TOPSIS, VIKOR, PROMETHEE, ELECTRE, or DEA. Also, it is necessary for stakeholders to validate whether technically robust rankings have social credibility and institutional acceptability. Thus, fuzzy and hybrid AHP models should be viewed as enhancing methodology rather than providing automatic resolutions to problems associated with expert bias, rank reversal, and scale sensitivity. Therefore, their reliability must be validated through robustness testing, which includes transparency in all aspects of the test and through contextual validation.

In addition, criticism has been directed toward the Consistency Ratio, which is used in conjunction with the AHP to verify logical coherence, and the arbitrary limit of CR of less than 0.10. Some argue that too strict an adherence may exclude potentially useful, though imperfect, information from experts [14], while other critics suggest that too loose an approach may call into question the legitimacy of critical high-stakes energy policy decisions, leading to the need to apply this measure on a case-by-case basis.

The ratio of consistency (CR) should be a context-based (diagnostic) tool when it comes to evaluating renewable energy planning instead of being an absolute standard to judge whether or not the results are "correct". The traditional $CR < 0.10$ is still a good way to evaluate the rationality of AHP pair-wise comparison, but the application of this criterion needs to be based on the decision problem's scale, level of uncertainty, number of stakeholders, and potential consequences of the decisions [14].

In high-risk scenarios like national energy roadmaps, renewable energy auctions, large-scale solar and wind site selection, it would be preferable to have a stricter threshold, for example: $CR < 0.05$-0.08. As poor and inconsistent judgments may lead to costly investment errors, land-use conflicts, or weak policy legitimacy [137]. However, for standard renewable energy technology selection and site-screening studies, a $CR \leq 0.10$ may deemed acceptable, given the criteria hierarchy is clearly defined and expert judgments are transparently documented [138].

In contrast to large-scale projects such as power plant construction, which require high levels of accuracy, exploratory workshops at an early stage, multi-stakeholder consultations with a real difference in opinion regarding the importance of certain criteria and goals permit tolerance toward a $CR = 0.10$ and 0.20 under specific conditions. On the other hand, a $CR > 0.20$ will normally indicate that there has been some type of error in either the elicitation process or the construction of the comparison matrix [138]. The practitioner should therefore revise the comparison matrix, elicit new judgments from experts, or apply methods to improve the consistency among expert opinions. Such flexibility in applying AHP methodology enables better utilization by practitioners in real-world decisions on renewable energy [137].

AHP is also limited by the fact that it assumes independent criteria in a hierarchy, which does not reflect the typical interdependent nature of renewable energy systems (for example, how economic incentives can influence the rate at which technology is adopted). The limitations on this have led to the development and application of the Analytic Network Process, which allows for consideration of feedback loops [139]. However, while ANP provides greater flexibility than AHP, due to the added complexity, it is not widely used for the same reasons. Also, issues related to data availability and transferability between contexts demonstrate that the results of an AHP study are specific to the context in which they were conducted; therefore, do not necessarily lend themselves to being transferred into other socio-technical or policy environments without some form of contextual adjustment and/or integration with tools such as geographic information systems (GIS) and/or life cycle assessments [140– 142]. To overcome these shortcomings, researchers have suggested several methodological improvements to AHP in the form of fuzzy and interval type-2 fuzzy AHP for more effectively quantifying linguistic ambiguity [80] and the use of methods to improve consistency and thus enhance reliability [144, 145] along with the use of hybrid weight determination methods to reduce subjectivity [146, 147].

Handling Uncertainty

The need to address inherent uncertainties when evaluating alternatives in complex decision-making environments (renewable energy) is significant. RES planning requires the use of a variety of datasets that are typically fragmented and subject to rapidly changing technology [134, 148]. The development of grey multi-criteria decision methods (Grey MCDM), which are based on grey systems theory, enables a systematic approach to the evaluation process under uncertainty in terms of missing, uncertain, or unknown partial information [149–152].

To address both the linguistic ambiguity as well as the subjective and imprecise nature of Expert Evaluations, Fuzzy Logic and MCDM methods are often integrated with each other [9, 153]. In this regard, Fuzzy AHP, Grey AHP, and other Hybrid formulations of AHP have proven instrumental in providing conventional MCDM methods with more reliability and flexibility in evaluating options [154–158]. Specifically, Fuzzy AHP has been shown to facilitate decision-making when linguistic ambiguity exists, and Grey AHP has been demonstrated to be most effective when there is either limited or missing data available. Together, these methodologies enable a more stable and realistic analytical methodology for renewable energy decision-making applications [157, 158]. Table 4, below, provides context on recent developments in decision-making methodology, and is a comparison between the advantages/limitations and uses of the Classical, Fuzzy, and Grey MCDM techniques. Additionally, it indicates that Fuzzy AHP and Grey AHP are two major enhancements to the AHP.

Table 4: Comparative Characteristics of Classical, Fuzzy, and Grey MCDM Approaches

Aspect	Classical MCDM	Fuzzy MCDM	Grey MCDM	References
Treatment of Information	Assumes complete, precise, and deterministic data	Models linguistic vagueness and subjective uncertainty using fuzzy sets	Addresses incomplete, indeterminate, or partially known data through grey numbers	[6, 99, 159]
Strengths	Simplicity, transparency, and widespread acceptance	Captures human judgment expressed in vague or linguistic terms	Effective under limited data conditions; robust in handling partial information	[3, 9]
Limitations	Sensitive to missing or uncertain data	Complexity in calibration and defuzzification	Less intuitive; limited methodological standardization	[5, 8, 11]
Typical Applications	Technology ranking, policy prioritization, resource allocation	Energy planning with expert judgments, supplier selection, environmental assessment	Renewable energy siting under scarce datasets, infrastructure planning, resilience analysis	[24]
Decision Robustness	High under well-defined conditions	Moderate–high when linguistic uncertainty dominates	High in uncertain, data-limited, or evolving environments	[11, 120]

Applications across Contexts

AHP has shown significant ability to be applied in many ways to renewable energy planning, based on numerous applications at different levels of governance and geographic scale. AHP is used in dense urban environments with tight physical constraints, in small-scale, decentralized rural energy systems, and at the national level in policy structures that govern how renewable energy can be deployed. The many uses of AHP illustrate its ability to deal with variously constrained and unique decision-making situations. Due to the limitations of space/land use and high density of the city, solar thermal and biomass were identified as the most suitable renewable energy options compared to wind [14]. Additionally, AHP has facilitated rooftop solar adoption through preference-based strategies in Greek municipalities [130] and facilitated the optimal placement of distributed solar PV and small-scale wind turbines within European cities such as Berlin, Copenhagen, and Amsterdam [8]. These examples demonstrate the spatial nature of AHP applications, including the role of competing land uses and population densities in planning [160–163].

In contrast, AHP has value for assessing small-scale renewable systems in rural areas and remote locations through a multi-criteria evaluation process for mini-grids, micro-hydro, solar home systems, etc. The limitations of rural or remote communities include: limited access to capital and/or infrastructure to support large-scale projects. AHP studies demonstrate that it ranks micro-hydro as the best option in rural Turkey due to the abundance of resources and cost-effectiveness [128], whereas AHP-based assessments of small-scale renewable systems rank solar PV mini-grids as the most viable alternative in Sub-Saharan Africa based on their lower operating/maintenance costs and scalability [18].

In rural India, AHP helped identify a hybrid solar-biomass system as being superior to either a single source of renewable energy or to other alternative sources of renewable energy for small-scale micro-grids, through multiple-criteria evaluation [10]. AHP's utility in evaluating renewable energy transitions in rural settings is further evidenced by its consideration of factors such as social acceptability and affordability in addition to technical feasibility, at a national level. It has also been utilized to prioritize energy resource development, assist with structuring competitive bidding processes for energy projects, and provide long-term strategic guidance to government planners involved in developing sustainable energy plans [164–167]; although most of these applications have been at the national level, within national sustainable energy and climate action plans (SECAPs), there is an increasing trend toward applying AHP-based decision-making tools at the local/municipal levels, as part of localized sustainability strategies [165]. As a result of this, researchers have recently applied AHP to new emerging areas that reflect changing energy policy priorities and needs, including, but not limited to, green hydrogen development and integration of storage into energy systems, thus linking new methodological innovations with energy transition roadmap demands [168–170]. The adaptability of AHP is apparent through comparison of the various uses of AHP across different settings, ranging from urban transitions to rural electrification and national policy frameworks, as indicated by Table 5.

Table 5: Comparative applications of AHP across urban, rural, and national energy planning contexts

Context	Typical Energy Options	Key AHP Criteria	Illustrative Outcome	Reference
Urban Planning	Rooftop solar, large scale solar and wind	Land-use, aesthetics, emissions, economic feasibility	Solar PV often prioritized due to compactness and environmental fit	[171, 172]
Rural Electrification	Mini-grids, solar home systems, micro-hydro, biomass	Affordability, maintenance, scalability, community acceptance	Solar PV mini-grids often dominate; hybrid solar-biomass effective	[173]
National Policy Frameworks	Wind, solar, hydro, biomass, geothermal	Cost, security, CO_2 reduction, jobs, political feasibility	Wind dominates in Turkey; solar in U.S.; hydro in China	[174, 175]

AHP within Hybrid Frameworks for Renewable Energy Planning

Although AHP is utilized in most renewable energy planning studies, it AHP has hardly been used as a lone tool. The systematic decomposition of complex renewable energy planning problems has made AHP an essential element in the vast majority of hybridized MCDM frameworks. Most renewable energy planning studies that employ AHP have paired it with another method to eliminate some of the deficiencies of each method individually. For example, rank reversal issues, scaling issues due to subjective judgments, and difficulties in managing large datasets are all common issues associated with MCDM methods that can be addressed through integration with AHP. As indicated by bibliometric analyses that examine renewable energy studies published between 2015 and 2025, the utilization of AHP in conjunction with other methods or tools was identified in approximately 62% of renewable energy studies that employed AHP. Specifically, it was found that AHP was integrated with TOPSIS, fuzzy sets, and GIS [176–178].

The growth of hybrid MCDM models has created a need for an overall framework or set of standards by which these models can be compared based on three main factors: reliability, usability, and contextual suitability. Combinations, such as AHP-TOPSIS, Fuzzy AHP, AHP-VIKOR, Entropy- AHP, and Grey-AHP, are all becoming more popular in renewable energy planning. However, it remains difficult to evaluate how well each performs relative to others due to differences in criteria selection, normalization methods, approaches to assigning weights, uncertainty, and validation techniques [8, 14].

Therefore, future studies need to develop a standardized evaluation system for hybrid MCDM models based on measurable parameters. Methodological transparency, reproducibility, computational complexity, spatial transferability, usability, rank stability, sensitivity robustness, and the ability to handle uncertainty are critical factors to these models' outputs. Such Standardized metrics would allow for more consistent comparisons of different hybrid configurations, and identify the most appropriate model configuration for a given renewable energy planning context [179, 180].

The above trend illustrates a double necessity of both methodological solidity and the need for policy-based decision-making in developing energy systems [13, 181]. The most used combinations of hybrid models are the use of AHP–TOPSIS to select technologies, rank sites, and prioritize resources as they leverage AHP to determine the weights of the criteria and TOPSIS to find the alternative that best approaches the ideal solution [104]. The second most influential form of hybridization is the combination of AHP with GIS for the spatial planning of energy.

In addition to providing an entirely technical application base for hybrid AHP models, which can be used to develop policy formulations and support various aspects of the governance process [182, 183]. Some examples of how AHP has been used in conjunction with other types of modeling frameworks to support policy development and long-term energy planning include AHP-DEA. This has proven very effective in assessing energy efficiency in terms of weighted policy, developing strategies to transition to a long-term net-zero carbon emissions economy, and participatory AHP-MCDM approaches that allow for multi-stakeholder negotiation and policy development transparently [184]. This increased utilization of hybrid frameworks and increased focus on developing policy-focused AHP applications, along with uncertainty management, represents a broader paradigmatic shift away from traditional technical assessments towards the strategic use of AHP for governance and long-term energy planning purposes [185].

Emerging Trends in MCDM Applications for Renewable Energy Planning (2020–2025)

The period between 2020 and 2025 was also an era of significant transition for the application of MCDM methodologies to renewable energy planning, primarily due to the increasing worldwide commitment to achieving net-zero emissions goals and the complex nature of moving toward a low-carbon economy [186, 187]. The time frame can be defined with a clear methodological trend of transition away from traditional stand-alone non-hybrid techniques that are data-poor, such as AHP and TOPSIS, toward hybrid and data-rich and contextually aware methods. Digitalization has been instrumental in this regard, as advanced analytics and artificial intelligence are now being used with MCDM [104, 105, 147]. For example, in combination with machine learning, Bayesian networks, and large-scale data optimization, can analyze huge amounts of real-time data sets, thereby reducing past criticism about AHP's subjective nature through the inclusion of empirical evidence within hierarchical decision structures [121].

This change in focus is critical because many of the factors affecting renewable energy systems are changing dynamically and cannot be evaluated with complete accuracy using static evaluation tools or a single set of input data for a particular project. Technology costs, conversion efficiencies, storage performance, grid constraints, policy incentives, land-use pressures, and climate-related hazards may change substantially over the lifetime of renewable energy projects, reducing the reliability of purely static AHP assessments [188]. Thus, relying solely on purely static AHP evaluations could lead to inaccurate results regarding the feasibility of renewable energy technologies/projects.

AI integrated MCDM frameworks represent an opportunity for improving the use of data driven modeling and machine learning (ML) capabilities. For example, ML models could be applied to model solar irradiance forecasts, wind speed variation forecasts, electricity demand forecasts, technological cost trajectories, climate risk forecasts, and infrastructure vulnerability forecasts [189–195]; whereas, the MCDM methods would transform those forecasts from dynamic output into static ranked inputs regarding which renewable energy technologies are most appropriate for which locations/sites or which alternative policies should be selected. Additionally, recent literature has illustrated the increasing adoption of geographic information systems (GIS)-integrated MCDM, fuzzy-MCDM, system dynamics-based MCDM, and AI-based decision frameworks as well as their potential benefits for enhancing adaptability within uncertain environments, particularly in regards to spatial planning, resilience assessments and long-term energy transitions [196, 197].

Therefore, AI is not an alternative to using AHP or other MCDM techniques in relation to this problem; rather, it is a supplementary empirical layer that improves decision-making by updating decision input data, identifying non-linear patterns in the data and increasing resilience of decisions to both technological advancements and extreme climate events. The above integration could assist in transforming AHP-based renewable energy planning exercises from static expert-driven processes into an adaptive, evidence-based, and climate-resilient decision support process [198, 199].

The bibliometric data indicate that greater than 70% of all post-2020 MCDM energy studies used some type of hybridization, illustrating a fundamental change of paradigm away from single tool dominance towards methodological pluralism. The development of these hybrid approaches is illustrated by many examples, which include GIS-AHP for site selection of solar and wind farms, fuzzy extensions of AHP for addressing expert uncertainty, and AHP-TOPSIS/VIKOR for robustly ranking alternative technologies [8,130]. Hybrid applications that combine AHP with advanced techniques, including AHP-neutrosophic logic and AHP-DEA, have emerged as well to address additional problems such as rank reversal and subjective weights, and reflect an increasing need for enhanced methodological reliability.

Energy decision-making has become a socio-political process and thus another important development beyond optimizing techniques is integrating stakeholders' views into multi-criteria decision analysis (MCDM) methods, and to this end, AHP is often used for participatory governance. The use of participatory governance in renewable energy can be seen through case studies across both Europe and Asia, and provide an example of how participatory decision-making frameworks can offer all parties involved (local community members, policymakers, and private sector investors) a common forum for engagement [200, 201]. The participatory decision-making processes for renewable energy are explicitly designed to incorporate social equity, environmental justice and cultural context into the process of implementing renewable energy development projects [1,128]. Thus, this is reflective of a larger trend that is developing throughout the field of sustainability science, toward a more inclusive and socially-based decision-making paradigm; one that supports global initiatives such as the United Nations Sustainable Development Goals [202].

In addition, many classical MCDM methods that are based on an assumption of stable preferences can be replaced by new MCDM techniques that allow for dynamic and adaptive decision-making processes. In particular, there has been an increasing trend of using MCDM in combination with system dynamics, which includes incorporating feedback mechanisms into models, enabling the real-time re-evaluation of decisions as a result of changes in policy, climate, markets, etc. This approach will become increasingly important when assessing the resilience of systems that may experience disruptions such as energy shocks, supply chain disruptions, or cyber-attacks [18, 202]. These trends are clearly reflected in the bibliometric map. Citations for AHP have increased three-fold since 2015; Hybrid AHP frameworks now account for more than 70 percent of all MCDM papers published after 2020 that relate to renewable energy; GIS linked AHP models dominate studies related to siting of both solar and wind, and also biomass; And Fuzzy AHP, has developed at the fastest rate, with the number of applications doubling from 2020 to 2024. Furthermore, the fact that top-tier journal articles are being written on MCDM represents a level of acceptance and impact among scholars of MCDM in this highly relevant area.

Policy Implications and Strategic Recommendations

The ability of AHP to convert complex and complicated quantitative analyses into a clear, understandable set of policies provides a framework for transparent, accountable decision-making for policymakers in order to reduce their reliance upon subjective judgments in policy development. AHP can be used as an important tool in developing national renewable energy roadmap initiatives, identifying those renewable energy technologies that are most worthy of receiving government subsidies or regulatory support, and ultimately, creating consistent and systematic methods for evaluating renewable energy options within government procurement processes and long-term energy master planning strategies. Furthermore, AHP can also provide a methodology for making strategic choices regarding how limited funding will be allocated in support of sustainable goals through a variety of renewable energy options (i.e. cost effective energy efficiency improvements and small scale modular solar PV installations [4, 204], large-scale wind projects and hybrid microgrid systems designed for resilience [205] by providing a method for systematically allocating funds to the most promising options [24,128].

AHP also provides important non-economic value to society in the realms of "energy justice" and "sociopolitical legitimacy". It is through this process that stakeholders' preferences are articulated in a way that ensures both equity in benefit sharing and burden distribution and, through such articulation, enables democratic governance of controversial policy initiatives [22, 206]. In addition, the decisions made using AHP contribute to achieving many aspects of global sustainability agreements and enables countries to focus on the most effective strategy to reduce emissions to meet their obligations under the Paris Agreement, and subsequently, to help achieve many of the other Sustainable Development Goals, especially SDG 7 and SDG 13 and to provide transparency of each country's contribution towards COP Roadmaps and strengthen their countries' commitment to climate action at the International level [207–221].

Research Gaps and Future Directions

While there have been many advances in applying AHP and broader MCDM methodologies to renewable energy planning, there are still several significant challenges or gaps in current research that need to be addressed as part of an effort to develop improved methodologies for both theoretical rigor and applied relevance for advancing global sustainable development agendas. Perhaps the most consistent criticism of AHP and other MCDM methodologies is their reliance upon expert judgment, while providing a basis for detailed and nuanced analyses of decision-making, at the same time, creates potential for subjective and biased assessments resulting from comparative pair-wise assessments, such as those identified by Salomon and Gomes [145], Hamka and Harjono [144] and Chan et al. [136]; furthermore, the larger the number of criteria or alternatives being assessed within the context of a single planning exercise, the greater the risk of inconsistent comparison ratios among experts.

The constantly changing and highly contextualized nature of renewable energy parameter characteristics, varying price fluctuations, changing technology, and varied availability of renewable resources, continuously generates a high degree of uncertainty for static assessments [104,222] despite various attempts by fuzzy AHP and probabilistic extensions to handle it. However, there are still large questions about how interpretable these approaches are to policymakers, particularly when dealing with deep uncertainty and ambiguity. Additionally, scalability is still an issue from a methodological standpoint, AHP is computationally intensive and requires input from experts, which limits its direct applicability within a country-wide or multi-country policy framework, although emerging integration of machine learning and/or big data analytics offers promising, if relatively immature, alternatives [107].

In addition to the above methodological challenges there also exists an even greater need for cross-disciplinary integration, as energy transitions have the characteristics of being profoundly socio-political, economic, and cultural in nature but many of the existing MCDM studies retain a technocentric focus and therefore privilege technical efficiency and cost over other important aspects such as social legitimacy, behavioral dimensions, and institutional barriers [132,146]. Therefore future research needs to be proactive in integrating knowledge from the social sciences regarding public perception, governance quality and distributional equity into the MCDM models developed. Furthermore, developing an interdisciplinary framework that integrates the optimization aspects of engineering with the viewpoints of political science, sociology, and economics will be necessary to comprehensively capture the complexity of these transitions [15,178] and ultimately enhance the social legitimacy and adoptability of MCDM-informed policy decisions by ensuring that the policy decisions are socially just and institutionally feasible. In addition, including socio-political aspects, such as public perception, procedural fairness, institutional trust, regulatory stability, permitting efficiency, land use conflicts, and costs and benefits sharing among stakeholders, need to be included as part of the main selection criteria in MCDM for renewable energy, rather than being considered as secondary qualitative criteria [223].

Technically viable renewable energy project proposals may be delayed, rejected, or terminated by local stakeholders when perceived to lack fairness or have limited connection with local socio-economic conditions. Institutional barriers will also negatively affect the potential realization of recommendations generated through otherwise strong multi-criteria decision-making based on AHP and hybrid approaches [224]. The inclusion of these factors could enhance the ability of renewable energy decision support tools to explain the nature of decisions made regarding renewable energy technologies; increase their legitimacy with stakeholders; and provide better guidance for decision makers in areas where societal opposition, instability of policy environments, or institutional weakness represent significant impediments to successful implementation of transitions to cleaner forms of energy [225, 226].

Additionally, the application of MCDM will have a vast horizon for expansion, specifically in addressing the urgent need for climate adaptation and resilience. AHP and MCDM currently focus mostly on selecting technologies, determining the suitability of locations, and making decisions about how to prioritize investments. However, future energy systems must not only be efficient but resilient to climatic shock and natural disaster disruptions as well as sociopolitical disruption [227-241]. As such, there is an imperative for developing MCDM models that provide for the integration of multiple hazards, time-based analysis to progress past current largely static evaluations, and effective linking with vulnerability and resilience indices at community, national, and regional levels. Additionally, effective cross-scale governance frameworks are necessary to bridge local decision-making with the global climate agenda [206, 225]. The transition from static evaluations to dynamic resilience-based planning, and thus from being static evaluators to being essential planning tools for governing the energy transition within a regime of great uncertainty, will be accomplished by addressing these key shortcomings.

Conclusion

With increasing emphasis on achieving net-zero targets in a rapidly changing environment, MCDM models, specifically AHP, has become increasingly important as a tool to support stakeholders in developing transparent, data-driven policy options through transforming complex, multi-dimensional trade-offs into actionable solutions. Through allowing structured stakeholder input and systematic prioritization, AHP supports increased legitimacy and robustness of all levels of energy policy development, including neighborhood, national, and international.

The hierarchical nature of AHP, the clarity of elicitation from stakeholders, and its potential compatibility with other methods to account for uncertainty and spatial variability make AHP a viable framework for use in neighborhood planning and national road-mapping. Future developments in this area will depend upon (1) treating uncertainty and bias rigorously, (2) developing standardized, participatory workflows for spatial analysis, and (3) explicitly integrating social equity objectives into AHP-based frameworks. When implemented, AHP-based frameworks have the potential to create credible, contextually relevant investment and policy decisions to achieve climate targets.

AHP can be applied to three different strategic frontiers. In terms of technology assessments, AHP will continually assess competing renewable energy options (solar, wind, hydro, geothermal, etc.) and hybrid renewable energy systems (i.e., combinations of two or more of the above). From policy formulation and investment prioritization perspective, AHP serves as an integrating structure to relate economic viability, the environmentally driven necessity for reducing emissions through sustainable energy practices and the social acceptance of renewable energy options; hence AHP has a significant role in facilitating global climate governance (the Paris Agreement, SDGs, UNFCCC COP decisions), by relating scientific analysis to societal concerns, thus assuring that the renewable energy transition is based on science and socially equitable.

To conclude, it has been demonstrated that AHP has advanced from being an analytical tool exclusively to serve as a governance enabling device for enhancing the evidence base of energy transitions through increased transparency and participation. The five key findings that arise from synthesizing these studies represent the primary contributions of this paper; they offer relevant information for those working in policymaking, planning, and practice:

- AHP is one of the primary MCDM tools used to evaluate the main criteria of renewable energy planning, including economic performance, technical viability, environmental sustainability, and social equity, in a systematic manner.
- AHP provides a systematic way of structuring expert judgment and the preferences of stakeholders and their trade-offs in terms of how they can be combined into policy decisions that are relevant to all geographic scales (urban, rural, national). It also provides a framework for balancing competing priorities for policymakers as well as developing contextually appropriate evidence-based strategies to support sustainable energy transitions.
- The combination of AHP with Fuzzy Logic, GIS, and other types of Artificial Intelligence (AI) driven analytical methods greatly enhances the capability of this method to manage and minimize uncertainty, to reduce the subjectivity involved in decision-making. The integration of these technologies allows for better modeling of the various spatial, technological, and socio-economic interactions that are typically present in renewable energy planning and therefore expands the applicability of AHP to numerous and complex data-intensive renewable energy planning contexts, as well as provides more reliable, evidence-based policy and investment options.
- Decision frameworks for global sustainability commitments, such as the Paris Agreement, COP Road Maps, and the Sustainable Development Goals, are critical to operationalizing these commitments at the local level by converting global sustainability commitments into locally actionable policy and implementation plans.
- To further advance the use of AHP as well as broader MCDM frameworks in decision making for the advancement of sustainable energy, future researchers will need to develop better ways to account for and mitigate expert bias and to foster greater inter-disciplinary communication across the technical, social and environmental realms; additionally, future researchers will be required to incorporate explicit consideration of climate resilient conditions into their decision support architectures. With embedded resilience metrics and cross-sectoral insights, the future of MCDM will have more robust, equitable, and forward-looking decision-making frameworks that will allow for the successful transition to long-term sustainable energy systems.

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