



Factor for Decision-Making on Renewable Energy Modes in Rural Properties

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Abstract: This article presents a systematic review on the application of multi-criteria decision-making (MCDM) methods and the implementation of the Analytic Hierarchy Process (AHP) method for weighting the Dimensions and their Factors in the selection of energy modalities for rural areas. The objective of the study is to identify the most commonly used approaches and criteria in the evaluation of energy alternatives, including renewable (solar, wind, biomass) and conventional sources, to meet the energy needs of rural communities in a sustainable manner. The article highlights the importance of MCDM in energy planning for rural areas, as these methods enable the integration of multiple factors in complex and diverse scenarios. It demonstrates the weighting of the Dimensions and their respective Factors, obtained through the AHP method and interviews with 29 experts in the field of renewable energy working in various professional sectors. The results indicate that the optimal energy solution depends on the local context, the specific needs of the community, and the availability of resources. The environmental and economic Dimensions were identified as the most relevant for decision-making regarding the choice of the energy modality used in the rural context of a developing country in Latin America. The study concludes that MCDM is important for promoting sustainability and efficiency in rural energy solutions, providing a structured approach to balancing multiple factors in decision-making processes.

Keywords: Multi-criteria Decision-making Methods; Rural Communities; Sustainability.



1. Introduction

Energy is currently recognized as one of the most vital economic and strategic resources. Consequently, energy strategies hold a prominent position in the concerns of many countries, whether they are producers or importers of energy [1]. A significant challenge facing the global electricity sector is the need to adapt to accommodate a substantial share of renewable energy sources [2]. Energy plays an essential and irreplaceable role in the modern world, with energy consumption serving as an indicator of societal and national progress, as well as advancements in modern industry and technology [3].

The increasing pursuit of alternative energy resources underscores the global interest to enhance energy production in a sustainable manner [4,5]. According to Shariff et al. [6], the quest for suitable sources of electricity generation is a key priority for national development, as fossil fuel resources are finite and have detrimental environmental impacts. However, uncertainties related to costs, energy storage, and the management required to implement renewable energy generation systems necessitate a robust management methodology to effectively inform decision-making.

Since the mid-19th century, energy supply has been primarily based on a centralized model consisting of large power plants strategically located near sources of primary energy supplies. These plants, connected to a transmission system, facilitate the transport of electricity to consumption centers [7]. In the 21st century, this centralized electricity production model has become the subject of ongoing discussions and modifications within the energy generation and supply system, thereby expanding energy distribution possibilities. However, this model also results in power losses during transport, a challenge that can be mitigated by reducing the distance between generation and load [8,9].

Decentralized generation can be implemented either as grid-connected (on-grid) or grid-disconnected (off-grid). In on-grid distributed generation, systems are integrated with the conventional electricity grid, allowing the excess energy produced to be injected back into the grid, thereby generating credits for the prosumer [10]. Conversely, off-grid systems operate independently of the electricity grid, typically utilizing storage solutions to ensure a continuous energy supply [11]. For rural properties, the implementation of decentralized generation systems can significantly contribute to sustainable development, whether through on-grid or off-grid solutions. This approach can enhance access to these technologies for small rural producers, thereby promoting diffusion, increasing efficiency, and reducing costs.

Distributed energy generation from renewable sources offers several benefits, notably its low environmental impact, reduced energy losses, and diversification of the energy matrix [12,13]. The energy potential of renewable sources includes hydraulic, wind, biomass, and solar [14].



If properly harnessed, this potential could play a crucial role in expanding the electricity supply, particularly given the variety of viable technologies for decentralized energy generation.

In this regard, the global trend towards distributed generation, especially in photovoltaic solar energy, is on the rise. According to data from the International Energy Agency (IEA), this sector experienced growth exceeding 59 GW by 2022 [15]. Similarly, the increase in electricity demand is a global reality, and Brazil is no exception. It is expected that by 2030, Brazilian electricity demand will increase by approximately 40% [15].

Given the above and considering the emerging energy transition, decentralized energy generation presents itself as an extremely important alternative for sustainable development. The challenge of choosing energy sources in the decentralized model is significant for all sectors of the economy and society, including households, businesses, industries, public buildings, and rural properties. The feasibility of photovoltaic systems, due to their linear expansion potential, lower costs, ease of installation, and maintenance, has made this technology the most widely chosen [16]. However, unlike other sectors, rural properties have greater resources to explore alternative energy sources, such as biomass, biogas, streams, rivers, and dams, as well as physical space for wind power systems.

This study aims to identify, map, and analyze decision-making frameworks for selecting renewable energy sources in rural properties. Through a systematic literature review and bibliometric analysis, the research explores the application of Multi-Criteria Decision-Making (MCDM) methods to assess economic, environmental, social, and technical factors influencing energy choices. The findings contribute to the development of structured methodologies that support sustainable energy transition in rural areas by optimizing resource allocation, reducing environmental impact, and promoting long-term energy security.

The objective of this research is to analyze and evaluate the criteria that support decision-making in the implementation of renewable energy systems in rural properties. By identifying the most suitable energy modalities for the characteristics of the studied regions, the study aims to address the lack of clear guidelines and specific tools that facilitate the selection and adoption of renewable energy solutions by rural property owners.

2. Methods

This study follows the Systematic Literature Review (SLR) process proposed by Galvão and Pereira [18], which consists of 8 steps: (1) developing the research question; (2) searching the literature; (3) selecting articles; (4) extracting data; (5) assessing methodological quality; (6) synthesizing the data (meta-analysis); (7) assessing the quality of the evidence; and (8) writing up and publishing the results. Firstly, it was essential to review the adopted methodology, specifically bibliometrics. According to [19] bibliometrics is a procedure designed to quantify the artifacts of written communication. In alignment with this, [20] emphasizes that the method



also aims to assess the performance of research and publications conducted by individuals. For the preliminary selection of keywords, the PICO method was utilized, as described in [21], and adapted to the research model using the variation known as PIO. This led to the formulation of the search strings: String = P <and> I <and> O; or the alternative String P <and> I <and> O (Rate <or> proportion <or> average <or> ratio). This approach aimed to define the terms to be used for the search. The initial results provided an overview of the topic, emphasizing the word "Energy." In terms of the central study method, the term "Strategic Management Tools" and the context "Rural" emerged as significant. These keywords were then translated and cross-referenced for bibliometric analysis. This composition of search strings guided the subsequent stages, as illustrated in Figure 1. Following this, the keywords were selected and immediately cross-referenced for bibliometric analysis.

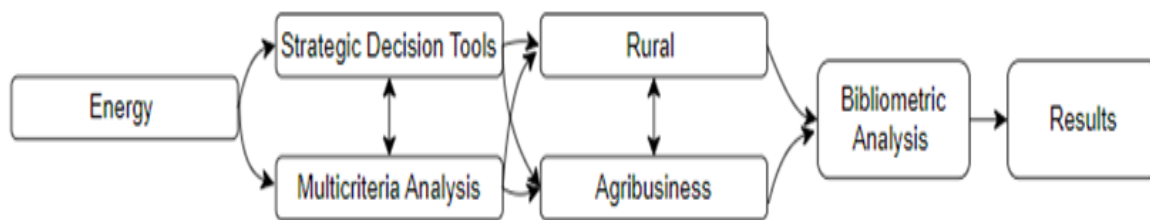


Figure 1. Keyword calibration for SLR search.

During the cross-referencing process, it is important to highlight that the keyword "Energy" holds greater significance than the other keywords due to its centrality in the research topic concerning energy matrices. The terms "Strategic Decision Tools," "Multicriteria Analysis," and "Agribusiness" represent management concepts whose relevance to studies and applications of energy modalities in rural areas within intellectual, cultural, and social frameworks should be examined, as indicated by the bibliometric database.

Data collection was carried out in January 2024 on the platforms Emerald, Web of Science, Scopus, and IEEE Explore. The keywords were entered into the advanced search function of each platform to ensure that only relevant articles were retrieved. These articles were published within the specified time frame and included keyword 1, keyword 2, and keyword 3 in their titles, abstracts, and/or keywords. Utilizing the search string 'energy OR electricity' in any field, and 'strategic decision tools' OR 'multicriteria analysis' in any field, and 'rural OR agribusiness' in any field (titles, abstracts, and/or keywords), a total of 1,218 articles were identified.

The study was conducted using eligibility criteria for the selection of articles, which consisted of analyzing each one by answering the following exclusion questions:

Q1: Does the article address a decision regarding an energy modality? (A: Yes/No)

Q2: Is it discussed in the context of rural areas or agribusiness? (A: Yes/No)

Q3: Does it apply any strategic decision-making tool? (A: Yes/No)



If any of the answers to the questions were 'No,' the article was excluded from further consideration. Following this analysis, a total of 109 articles relevant to the researched topics were identified. These articles were then examined in greater depth to extract the following data:

Q4: Where was the article applied (Country/Region)?

Q5: What are the decision criteria/variables?

After an in-depth review of the articles, 32 titles were deemed eligible due to their strong thematic connection with the content of this research. These articles provided the foundation for both the writing of this document and the selection of the methodology used to analyze data in future stages of the study.

The second phase of the research focuses on expert opinions regarding decision-making factors. For this purpose, the Analytic Hierarchy Process (AHP) method was applied to weigh the factors. A weighting questionnaire was administered to 29 experts who voluntarily participated in the study. This questionnaire assessed the relative importance of four key dimensions: Social, Environmental, Technical, and Economic. To understand the impact of each dimension, pairwise comparisons were conducted to determine their relative weights. However, these dimensions encompass multiple factors, forming a decision tree. Therefore, factors also required pairwise comparisons within their respective dimensions to establish their relative importance. This process is detailed in the questionnaire provided in Annex 1.

During the interviews, experts evaluated the importance of each dimension—Social, Environmental, Technical, and Economic—along with their respective factors, using the typical pairwise comparison scales of AHP. The results of this stage indicate the relative relevance of each dimension and factor in the decision-making process. They also provide a foundation for the subsequent stages of the framework, enabling a more precise and data-driven analysis of available energy alternatives for rural properties.

3. General Overview of the Articles

This chapter provides a general overview of the articles addressing this topic, analyzing academic and technical contributions on decision-making frameworks, as well as the feasibility of different renewable energy sources—such as solar, wind, and biomass—on rural properties. The bibliometric study was conducted using VOSviewer® software, utilizing 1,218 articles to establish correlations between keywords, identify the most relevant authors on the subject, and analyze co-authorship among the records retrieved from the database searches.

The analysis of Figure 2 illustrates the interconnection of keywords used by authors and their selected journals in the first research filter. These keywords were subdivided into 10 characterization clusters.

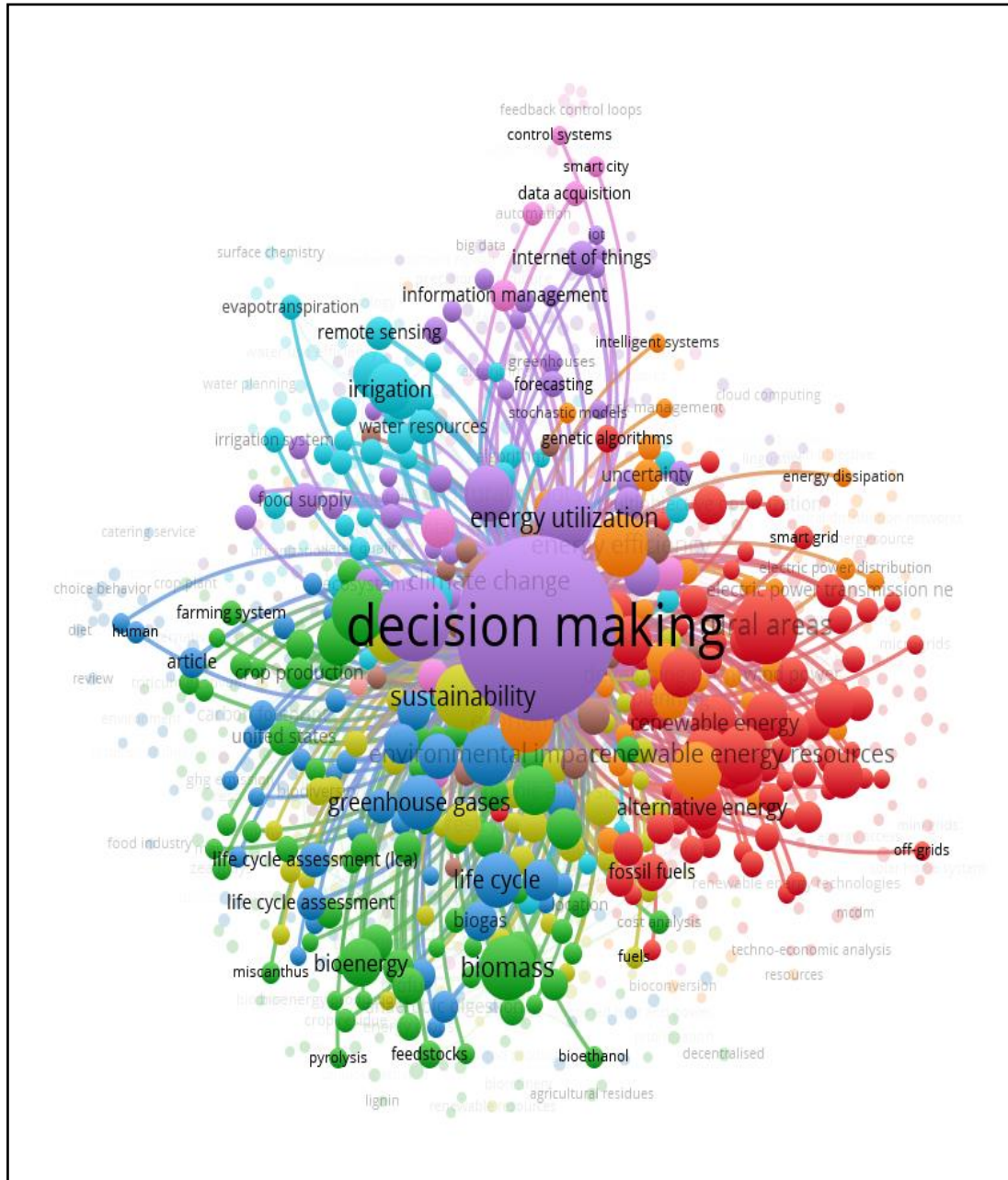


Figure 2. Correlation Between Keywords.

The five main clusters, ranked by importance, are: Decision Methods (Purple), which serves as the foundation of the study and connects to all other clusters, as the research centers on decision-making methods. The second-largest cluster, Energy Efficiency (Orange), closely relates to this focus. Strongly interconnected with both are Environmental Impact (Blue) and the topic of Sustainability (Yellow), ultimately leading to the primary application focus of this research—Rural Areas (Red), as demonstrated in Figure 3.

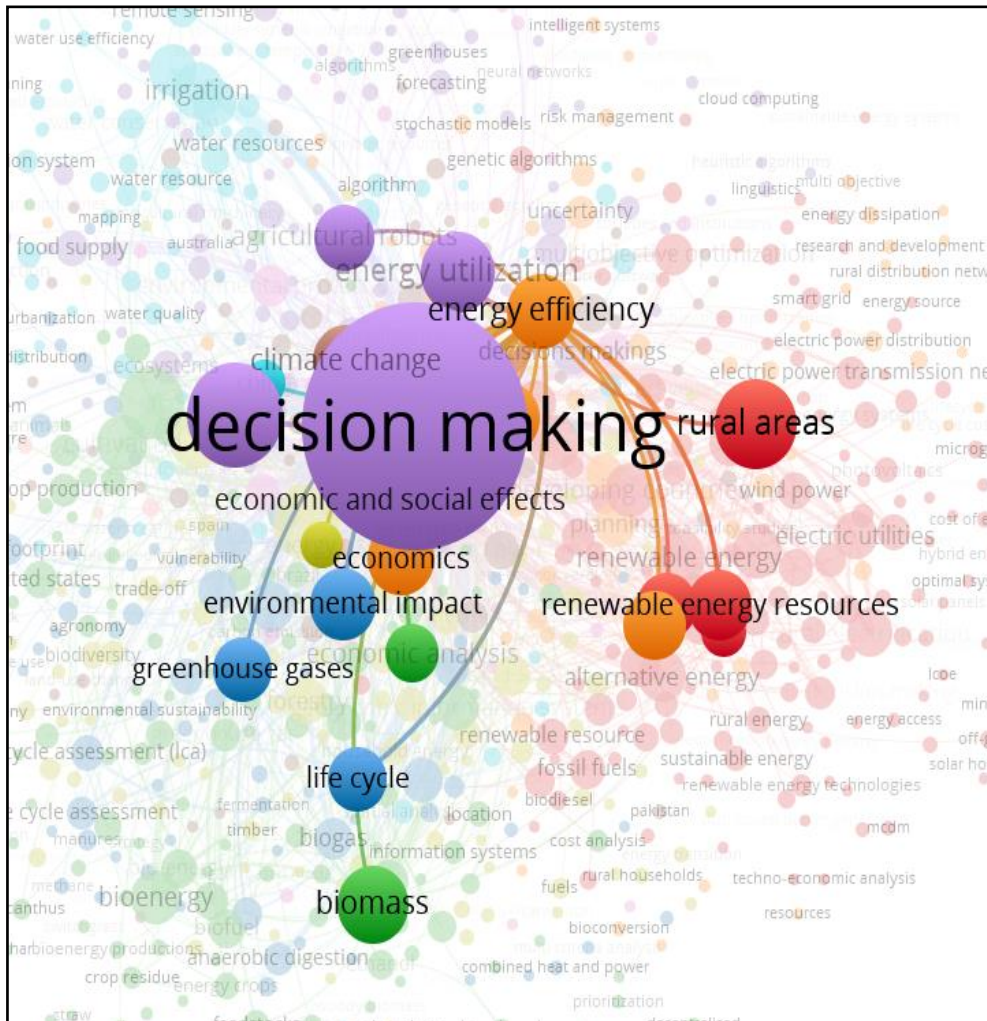


Figure 3. Main Keyword Clusters.

The correlation among the 1,218 articles demonstrates the existence of 22 linkage clusters, highlighting the cooperation between different research groups on the topic. Additionally, Zhang [22], Wang [23], and Yang [24] stand out as the most representative authors in this field. Another relevant observation is the existence of several research groups with limited collaboration within the larger network formed by the key authors mentioned above.

The analysis of Figure 1 supports one of the pillars of this Systematic Literature Review (SLR), where keyword data extraction through VOSviewer® highlights the main keywords identified in the abstracts of this SLR: Decision Methods, Sustainability, and Energy Utilization. Bibliometric analysis also enabled the identification of the countries with the highest scientific citations on the subject.



Melo (2017) [25] emphasizes the complexity of rural development, emphasizing its multidimensional nature, which involves a variety of activities and the interaction of diverse social relationships and stakeholders. This perspective underscores the importance of effective management in minimizing the depletion of non-renewable resources and promoting the sustainable use of renewable resources. To achieve balanced and sustainable rural development, it is essential to implement mechanisms for the reutilization of renewable resources, as well as encourage the adoption of practices that foster the conservation of non-renewable resources. This requires establishing a sustainability cycle that considers the relationship between humanity and nature as fundamental. In this context, the development of a decision-making model for energy matrices is crucial, as the selection and implementation of renewable energy sources in rural areas play a key role in advancing and adopting these technologies. This is essential for meeting national energy conservation targets and reducing emissions [26].

Some authors have sought to develop models to assist in decision-making regarding different modes or technologies for electricity generation. Rojas-Zerpa et al. [27] present and discuss mathematical methods used in planning electrification in rural environments with decentralized energy sources. The study aimed to determine the best formulation for the multicriteria decision-making problem, aligning robust planning alternatives with the specific characteristics of each location and the needs of local residents. A literature review was conducted on publications from the late 1970s to 2013, analyzing approximately 120 studies on energy planning topics such as electricity supply, transportation, and buildings. However, the authors focused specifically on research related to rural electrification planning using decentralized energy sources. Additionally, other energy supply modalities were identified, including the expansion of the conventional electricity grid as an alternative to decentralized supply. The research areas covered include energy planning, distributed generation, sustainable energy, multi-objective and multicriteria decision-making, and rural electrification. The authors identified a paradigm shift beginning in the 1990s, in which decision-making problems started incorporating multiple objectives or evaluation criteria. Thus, the study provides evidence that multicriteria decision-making models offer more satisfactory solutions to meet the current demands of decentralized energy planning in rural environments.

Kumar et al. [28] state that with the growing focus on sustainable development, energy planning has become increasingly complex due to the need to consider multiple evaluation parameters—such as technical, social, economic, and environmental factors—challenging decision-making particularly in rural communities. Another issue raised by the authors is that renewable energy systems face topographical limitations, further complicating energy planning. To address this, the study presents a review of various Multi-Criteria Decision-Making (MCDM) techniques, the progress achieved through the application of



renewable energy in MCDM methods, and future perspectives in this field. Additionally, it highlights different performance indicators that can be used, such as job creation, climate risks, and technology maturity. The study demonstrates that decision analysis using robust methods can overcome the challenges posed by the extensive number of evaluation indicators and the specific characteristics of each renewable energy system, even in fragmented electrification scenarios. The review makes it evident that MCDM has become a popular tool due to the flexibility it provides to decision-makers, enabling them to improve actions while simultaneously considering all criteria and objectives.

Abdel-Basset et al. [3] conducted a case study in Egypt, evaluating sustainable bioenergy production technologies. Methodologically, the authors developed a comprehensive protocol in which experts and decision-makers use linguistic terms to express their preferences during the decision-making process, prioritizing the dimensions that impact the sustainability of bioenergy production technologies. The study highlights the challenges in identifying the best bioenergy production technology and establishing priorities, as multiple dimensions must be considered, including environmental, technical, economic, and social factors, along with their respective sub-indicators. The authors employed a hybrid Multi-Criteria Decision-Making (MCDM) technique and addressed uncertainties using Trapezoidal Neutrosophic Numbers (TNNs). First, the authors applied the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to determine the relative importance of the dimensions and their sub-indicators (weighting). In the second stage, alternatives were ranked based on their Distance from the Average Solution (EDAS). The feasibility of the proposed protocol was validated through an illustrative case study, considering seven bioenergy production technologies, demonstrating the advantages of hybrid MCDM techniques. Additionally, a sensitivity analysis was conducted to verify the stability of the developed framework. The results provided valuable insights for decision-makers regarding energy policies, revealing that the most suitable sustainable bioenergy option was the conversion of agricultural and municipal waste into biogas, followed by the transformation of oilseed crops into biodiesel. Finally, the authors suggest that company managers and local community members be included in the evaluation process and recommend using the protocol for public environmental assessment, renewable energy source selection, and green supplier selection.

Studies conducted in Egypt indicate that the country produces a significant amount of biomass derived from four primary sources: agricultural waste, animal waste, sludge from wastewater treatment, and municipal solid waste [3,59]. This biomass offers a diverse range of applications, from direct heating in domestic and industrial contexts to the production of liquid or gaseous fuels and the generation of steam for electricity production. Although direct heating has historically been the most widely used application, biofuels and electricity generation are gaining increasing popularity among energy policy makers.



A variety of biofuels, such as ethanol, biodiesel, and advanced biofuels, can be derived from biomass to meet the needs of the transportation sector [3,60,61]. Petrelli et al. [44] emphasize that decentralized hybrid energy systems are promising and sustainable solutions for promoting socioeconomic and environmental development. However, they note that microgrid designs typically focus on economic factors (sometimes also considering reliability or environmental aspects), and costs are traditionally estimated by approximating the system's multi-year operation with a one-year approach, without considering long-term effects. The authors aim to propose a multi-objective and multi-year method for planning microgrids in the Global South, considering socioeconomic impacts (net present cost, job creation), safety (public lighting coverage), and environmental factors (carbon emissions, land use), while considering the entire multi-year life cycle of the project (demand growth and asset degradation). The study employed an algorithm called A-AUGMECON2 in an isolated community in Uganda. This approach effectively quantified the trade-offs between long-term local impacts, providing support for local policymakers to foster more informed actions. It became evident that aligning environmental goals with economic objectives is achievable and that the financial impact of public lighting is not significant, encouraging its implementation in electrification projects. In contrast, the study indicates that improved land use and job creation lead to considerably high economic and environmental costs, necessitating trade-offs for decision-makers. Finally, the authors suggest evaluating the stochasticity of long-term scenarios, integrating different investment stages throughout the project's life cycle, and applying the methodology to various energy systems to support decision-makers and benefit the studied communities.

Peng et al. [45] highlight that the selection of new energy sources in rural areas contributes to achieving national goals for energy conservation and emission reduction. The article proposes the creation of a decision support methodology to assist in the selection of new energy sources in rural areas, considering the reliability of information and the non-compensation of criteria. The authors introduced Z-numbers to describe the assessment information of new energy sources and to identify the reliability of this information. Classification relations were also established, and the procedures for aggregation and classification exploration were demonstrated to address the non-compensation among the new energy evaluation criteria (outranking models). Additionally, the authors evaluated two empirical cases of new energy selection in rural areas of Liangping District and Rudong County in China. The research revealed that biomass energy and wind energy were the most suitable for the development of both regions and that the proposed framework enhances precision in decision-making process. The authors suggest utilizing machine learning algorithms to consider more complex factors and large data sets, as well as employing Z-numbers and outranking models for portfolio optimization, credit risk assessment, and virtually selecting products.

Table 1 shows the 32 articles selected from the SLR, along with their title, year, country of application of the study or first author and the publication vehicle.



Table 1. Selected articles in SLR.

Year	Title	Authors	Country	Journal
1998	A multiobjective approach to rural energy policy analysis	[25]	Canada	Energy
2011	Optimization methods applied to renewable and sustainable energy: A review	[26]	Spain	Renewable and Sustainable Energy Reviews
2012	Alternative Energy Options for India—A Multi-criteria Decision Analysis to Rank Energy Alternatives using Analytic Hierarchy Process and Fuzzy Logic with an Emphasis to Distributed Generation	[27]	India	Conference Proceedings 2012 38th IEEE Photovoltaic Specialists Conference, 2012
2012	A multicriteria approach to sustainable energy supply for the rural poor	[28]	Colombia	European Journal of Operational Research
2014	Multicriteria analysis of agricultural raw materials: A case study of BSBIOS and PETROBRAS BIOFUELS in Brazil	[29]	Brazil	Energy Policy
2014	Methodologies, technologies and applications for electric supply planning in rural remote areas	[30]	Spain	Energy for Sustainable Development
2015	Sustainable and renewable implementation multi-criteria energy model (SRIME)—case study: Sri Lanka	[31]	Spain	Energy Environ Eng
2016	Patterns of attention to renewable energy in the British farming press from 1980 to 2013	[32]	Ukraine	Renewable and Sustainable Energy Reviews
2016	Multi-criteria assessment of hybrid renewable energy systems for Nigeria's coastline communities	[33]	Nigeria	Energy, Sustainability and Society
2016	EU biofuel policies: Income effects and lobbying decisions in the German agricultural sector	[34]	Germany	Renewable Energy
2016	Assessment of biomass energy sources and technologies: The case of Central America	[35]	Spain	Renewable and Sustainable Energy Reviews
2017	A review of multi criteria decision making (MCDM) towards sustainable renewable energy development	[36]	China	Renewable and Sustainable Energy Reviews



2017	A multi criteria decision making framework for sustainability assessment of bioenergy production technologies with hesitant fuzzy linguistic term sets: The case of Iran	[37]	Iran	Renewable and Sustainable Energy Reviews
2017	Factors influencing the adoption of biogas digesters in rural Ethiopia	[38]	Ethiopia	Energy, Sustainability and Society
2018	Robust multi-objective optimization of a renewable based hybrid power system	[39]	Brazil	Applied Energy
2018	Planning renewable energy in rural areas: Impacts on occupation and land use	[40]	Portugal	ENERGY
2019	Using methods of Multi-Criteria Decision Making to provide decision support concerning local bioenergy projects	[41]	Germany	Socio-Economic Planning Sciences
2019	Justification of solar home system in rural Bangladesh based on risk indicators: An integrated multi-criteria decision-making approach	[42]	China	International Journal of Renewable Energy Research
2020	Multi-Criteria Method for Sustainable Design of Energy Conversion Systems	[43]	France	Sustainability
2021	Development of a hybrid multi-criteria decision-making approach for	[3]	Egypt	Journal of Cleaner Production
2021	A novel multi-objective method with online Pareto pruning for multi-year optimization of rural microgrids	[44]	Italy	Applied Energy
2021	A decision support framework for new energy selection in rural areas from the perspectives of information reliability and criterion non-compensation	[45]	China	Energy
2021	A new decision-making process by integration of exergy analysis and techno-economic optimization tool for the evaluation of hybrid renewable systems	[46]	Iran	Sustainable Energy Technologies and Assessments



2021	Selection of renewable energy in rural area via life cycle assessment-analytical hierarchy process (LCA-AHP): A case study of Tatau, Sarawak	[47]	Malaysia	Sustainability
2021	Characterization of technological innovations in photovoltaic rural electrification, based on the experiences of Bolivia, Peru, and Argentina: Third generation solar home systems	[48]	Spain	Sustainability
2021	A multi-criteria sustainability assessment for biodiesel alternatives in Spain: Life cycle assessment normalization and weighting	[49]	Spain	Renewable Energy
2021	Solving a multiple user energy source selection problem using a fuzzy multi-criteria group decision-making approach	[50]	Tunisia	Energies
2021	Development of a hybrid multi-criteria decision-making approach for sustainability evaluation of bioenergy production technologies: A case study	[3]	Egypt	Journal of Cleaner Production
2021	A decision support framework for new energy selection in rural areas from the perspectives of information reliability and criterion non-compensation	[45]	China	Energy
2022	A decision-making and planning optimization framework for multi-regional rural hybrid renewable energy system	[51]	China	Energy Conversion and Management
2023	Energy futures of representative Swiss communities under the influence of urban development, building retrofit, and climate change	[52]	Switzerland	Sustainable Cities and Society
2023	Technology evaluation for biogas production from animal waste in circular carbon economy: A complex spherical fuzzy set-based decision-making framework	[53]	Iran	Bioresource Technology Reports
2023	Technically efficient, economic and environmentally benign hybrid	[54]	India	Journal of Cleaner Production



	decentralized energy solution for an Indian village: Multi criteria decision making approach			
2023	Insights and Evidence on Energy Retrofitting Practices in Rural Areas: Systematic Literature Review (2012-2023)	[55]	Italy	Buildings

The 32 most relevant articles selected for this research were predominantly published from 2017 onward, with a strong presence in journals focused on sustainability, energy, and technology, such as *Sustainability* and *Energy, Sustainability & Society*. As illustrated in Figure 4, Iran stands out as the country with the highest impact, with three studies conducted by Seyed Alavi et al. (2023) [60], Khishtandar et al. (2017) [43], and Absullah-Al-Mahbub et al. (2022) [61].

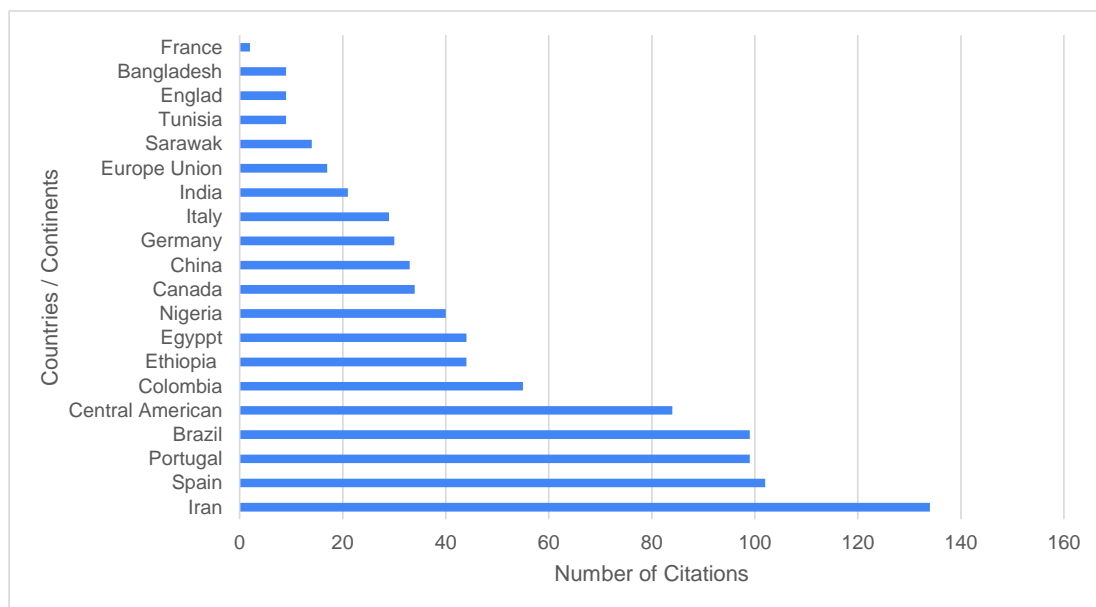


Figure 4. Citations by Countries/Continents of Study Application.

The research conducted in these countries focuses on decentralized energy generation in rural areas, with most studies emphasizing agro-energy. Agro-energy refers to energy derived from organic, non-fossil sources such as firewood, natural gas, ethanol, and biodiesel, where biomass produced through photosynthesis is converted into fuel energy. The articles also address the selection of electricity generation technologies using biomass and biogas.

An analysis of the 32 articles reveals that 16 employ some form of multi-criteria decision-making (MCDM) method to determine the most suitable energy source. Notably, the Fuzzy



and AHP methods are frequently used, along with the following renewable energy modalities, ranked in order of utilization: Biomass, Biogas, and Photovoltaic Panels.

Given the search for the most suitable energy modality for the characteristics of the studied regions, this research is justified by the need to understand and assess the criteria that assist in decision-making regarding the implementation of renewable energy systems in rural properties. Currently, the lack of clear guidelines and specific tools for evaluating and selecting the most suitable renewable energy options may hinder the adoption of these technologies by rural property owners.

4. Decision-Making Factors

4.1. Social Dimension

The social dimension is highlighted by authors from various perspectives, ranging from the impacts on the environment in which people live to job creation and regional development. The effect of the energy matrix on food security is an indicator related to social factors, particularly regarding biomass, as it concerns the impact of the energy matrix on the basic food basket. The production of raw materials can affect food security by altering land use and increasing prices [3,43].

Studies also mention the employment-generating potential of energy matrices, along with their ability to provide varying wage levels for the workforce involved. Jobs can be generated directly through project implementation, manufacturing, installation, operation, and maintenance phases. On the other hand, jobs can also be created indirectly, due to the demand for input supplies, the recruitment of professionals with expertise in energy matrix development, financing companies, accountants, and other related roles.

Another social aspect to be evaluated is the contribution of energy modality to regional development, including poverty reduction, energy provision for underserved regions, improvements in quality of life, and infrastructure development in remote locations. Furthermore, it is essential to assess whether governmental support exists for the evaluated energy strategy, through incentives such as tax exemptions, guarantees, credit programs, and research investments. This factor is also related to the potential integration of the modality into the national energy matrix.

Finally, authors address social acceptability factors, assessing the extent to which local residents accept the impacts of each energy modality. This acceptance is also linked to aesthetic harmony, noise generation, and the perception of dependence or independence on certain energy sources, particularly non-renewable ones.

The Social Dimension is described by three key factors, whose descriptions and supporting authors are presented in Table 2.



Table 2. Social dimension factors

Factor	Description	Authors
Impact on the local community	Community participation in the decision-making process. Local employability.	[3,25,28–30,32,34,37,38,40,41,44,45,48,50,54]
Social Equity	Levels of understanding regarding alternative energy modalities. Education programs for farmers and communities.	[3,29,35,37,38,43,48,54,63]
Education and Awareness	Highlight the environmental benefits of alternative energies, including the reduction of greenhouse gas emissions, minimization of pollution, and preservation of natural resources.	[34,37,41,43,48,54]

4.1.1 Impact on the Local Community

The availability and access to clean, reliable, and affordable energy services—such as solar energy, biogas, and biomass—are fundamental not only for solving local challenges but also as a key condition for improving the economic and social well-being of citizens. This includes increased productivity, poverty reduction, and economic growth promotion [63].

In Greece, significant advantages in job creation through renewable energy sources have been highlighted, as they tend to be more substantial compared to fossil fuel-based energy production [64]. The study by [65] concludes that a significant portion of stakeholders involved in implementing and using renewable energy sources is actively engaged in the establishment of energy facilities, which naturally influences their perspectives.

Although local authorities generally benefit directly and play a crucial role in facilitating the adoption of renewable energy in their regions, local associations, particularly those focused on environmental conservation or cultural heritage, have frequently opposed the construction of such projects, often without success. Local businesses may experience both positive and negative impacts from wind farms and solar power plants. These facilities can drive development and job creation, but they may also pose challenges to tourism and existing economic activities.



4.1.2 Social Equity

When an isolated rural community gains access to electricity, its residents become dependent on this resource, and any service disruptions can lead to severe consequences. Therefore, it is imperative to develop methods for creating resilient energy production systems that ensure a constant supply of electricity to these communities [45].

4.1.3 Education and Awareness

The level of awareness and understanding of different renewable energy sources can vary from country to country and even within regions of the same nation. The population's knowledge about renewable energy sources, their opportunities, and willingness to adopt them is influenced by multiple factors. Additionally, the readiness to implement these technologies is subject to various external and internal conditions [66].

4.2 Environmental Dimension

Abdel-Basset et al. [3] emphasize that economic development must be balanced with environmental concerns. It is essential to assess the potential degradation of soil quality resulting from raw material production for energy generation, including erosion effects, loss of soil fertility, and reduced water retention capacity. Land-use changes must also be considered, as raw material production for energy generation—such as biomass—can alter cropping systems, impact food security, and affect the overall development of rural properties. Environmental evaluations may include measurements of pesticide applications, the number of cultivated crops, and eutrophication levels. The Environmental Dimension is described by three key factors, with their descriptions and supporting authors presented in Table 3.

Table 3. Factors in the environmental dimension

Factor	Description	Authors
Reducing Emissions	Greenhouse gas emissions associated with each modality. Contribution to environmental sustainability.	[3,28,31,37,45,48–51,53,68]
Impact on Biodiversity	Assessment of the impact on cultivated areas and surrounding environments. Preservation measures implemented.	[3,28,37,40,41,44,45,48,49,53,62]



Sustainable use of resources	Consumption of natural resources by alternative energies. Potential for recycling and reuse.	[3,25,32,33,37,40,41,43–45,48–51,54]
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4.2.1 Emission Reduction

The assessment of emission reduction focuses on the environmental consequences associated with the use of alternative energy sources in agriculture. It considers greenhouse gas emissions from agricultural operations, comparing the impacts of conventional and alternative energy sources. This factor aims to quantify and qualify the contribution to climate change mitigation.

As early as 1994, research in Brazil identified significant potential for sustainable energy development, given the country's renewable energy resources, which could significantly reduce CO₂ emissions [69]. Thus, innovation in alternative energy production can be a key CO₂ emission reduction agent, either through the development of alternative energy sources or by improving energy efficiency using hybrid systems and bioenergy [70].

4.2.2 Impact on Biodiversity

The biodiversity impact analysis examines how the implementation of alternative energy sources can affect biological diversity in agricultural areas and surrounding ecosystems. It evaluates effects on local species, natural habitats, and ecosystems. Strategies to preserve or enhance biodiversity are considered an integral part of this factor.

The production of raw materials for bioenergy requires more cultivated land, reducing forested areas and altering crop management, cultivation systems, food security, land use, and rural development [43]. Additionally, the potential conflict between biodiversity conservation and energy generation shows favorable aspects for wind and photovoltaic solar energy compared to bioenergy. However, key global biodiversity areas are increasingly threatened by the expansion of renewable energy developments [71].

4.2.3 Sustainable Resource Use

This factor addresses the natural resource consumption of alternative energy sources, evaluating the sustainability of their use. It considers the efficiency of raw material, water, and other resource utilization for the production and operation of alternative energy systems. Additionally, it analyzes recycling and reuse practices associated with these technologies.

According to [72], the integration of energy systems using different energy modalities is a key element in the transition to renewable energy systems. However, [73] argues that optimizing



resource use is highly specific, as it depends on the intrinsic relationship between resource availability, energy potential, and geographic location.

Moreover, it is crucial to consider water consumption for raw material production. In regions facing water scarcity, the development of irrigation systems may be required, increasing costs and reducing water availability for both humans and wildlife [54].

4.3 Technical Dimension

The technical dimension for evaluating energy modalities in rural properties is widely discussed in the consulted literature, with its factors aiming to quantify the influence of technology on the selection of these energy matrices.

The first aspect to consider is technological maturity, meaning the need to use methods suitable for the country's industrial capacity. This capacity includes equipment availability, spare parts supply, and compliance with the required technical standards. Additionally, the development of technologies necessary for the chosen energy modality must align with national research priorities [3,43]. Table 4 presents the Technical Dimension, also described by three key factors.

Table 4. Technical dimension factors

Factor	Description	Authors
Technological innovations	Levels of technology associated with alternative energy modalities. Investments in research and development.	[3,25,26,29,30,36,39,43,45,48,51,53,68]
Energy Efficiency	Comparison of energy efficiency between conventional and alternative energy sources. Technologies for energy storage.	[3,25,28–33,35,37,39,43,45,48–51,53–55,62,68]
Support Infrastructure	Availability of infrastructure for charging or refueling. Integration with electrical	[3,26,28–30,33,37,41,43,45,48,53,54,62,68]



	grids and transportation systems.	
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4.3.1 Technological Innovations

Santra (2017) [74] states that research in the field of energy innovation yields positive results in a country's economic growth indicators. In 2001, the World Energy Council affirmed that technological innovations are crucial for improving quality of life, enhancing energy production systems, transportation, and overall efficiency (World Energy Council, 2001). Thus, technological innovation plays a key role in assessing energy consumption and ecological footprint, as technological advancements enhance energy efficiency, reduce energy consumption, and mitigate the environmental impact associated with energy use.

4.3.2 Energy Efficiency

According to Özcan M. and Özkan U. (2018) [75], energy efficiency is defined as achieving the same output with the same or lower energy consumption. Another important aspect to consider is the predictability of energy matrix performance, meaning whether there will be changes in operational patterns. Additionally, the duration for which an energy system can operate at full capacity and the reliability of the system in producing energy under specific conditions over a certain period must be assessed. The energy generation potential is also a key factor, as it determines the amount of energy a given energy matrix can produce.

4.3.3 Support Infrastructure

For the implementation of renewable energy sources, the existing energy infrastructure should be leveraged whenever possible. However, it is also necessary to develop a smart grid with greater storage capacity, as the intermittent nature of electricity supply from renewable sources requires grid modernization and the deployment of new communication technologies to promptly detect potential obstacles [76].

4.4 Economic Dimension

According to Abdel-Basset et al. (2021) [3], this dimension pertains to the economic sustainability aspects of the evaluated energy alternative, encompassing the entire process from construction to production and the actual consumption of energy by the end user. Furthermore, it highlights economic parameters related to the operation and maintenance of the energy source. This dimension includes five factors detailed in Table 5, along with the authors of the systematic literature review (SLR) who reference them.

Some factors observed in the SLR articles include capital, maintenance, and operational costs; acquisition of equipment, facilities, engineering services, and ancillary works; factory



profitability, employee earnings, farmers' rights, heating material operational costs, regional economic aspects, and the reliability of initial planning; and the challenge of providing quality energy at minimal cost while adding value to shareholders' investments in energy utilities. However, a universalization of these factors was adopted as presented in Table 5.

Table 5. Economic Dimension Factors

Factor	Description	Authors
Implementation Cost	Initial investment in alternative energy modalities. Associated operational costs.	[28,29,31–33,36,41,43,45,45,47,48,51,54,63,68]
Economic efficiency	Cost comparison between conventional and alternative modalities. Profitability for small and medium-sized farmers.	[25,28–30,35,36,43–45,49–51,53,77]
Government incentives	Policies for subsidies or incentives to promote the adoption of alternative energies. Availability of credit lines.	[28,32,33,37,38,41,43,48,53]
Macroeconomics	Influence of government monetary and fiscal policies on the transition to alternative energies in agriculture.	[3,3,29,30,34,37,41,44]
Microeconomics	Examine the effects on the labor market for small and medium-sized agriculture, considering changes in the demand for specific skills and the impact on employment rates.	[3,3,29,30,34,37,41]



4.4.1 Implementation Cost

Elia et al. (2021) [78] emphasize that one of the primary requirements for the implementation and commercialization of a technological innovation in the energy modal sector is its economic competitiveness. In other words, ensuring cost reductions is a key indicator of the technology's success. In 2015, the United Nations launched the Mission Innovation (MI) initiative during the United Nations Climate Change Conference (COP 21) in Paris, where 24 countries committed to increasing investments in the pursuit of clean technologies. Despite the high costs of implementation, the transition to clean energy is imperative in the current landscape. However, the study conducted by Rubin et al. (2007) [79] addresses the modeling of cost reductions as new experience is gained during implementation, utilizing a one-factor learning curve (OFLC).

Continuous innovation in energy technologies is a determining factor in reducing the costs associated with renewable energy technologies. As new advancements are integrated, production processes are optimized, efficiency is enhanced, and the performance of devices is improved. Moreover, investment in research and development drives the discovery of more effective and sustainable methods, contributing to the competitiveness and economic viability of renewable energy sources.

4.4.2 Economic efficiency

A widely used indicator today is the Levelized Cost of Electricity (LCOE). This approach presents the unit costs of electricity over the entire economic lifespan of a project and is commonly employed to assess feasibility and competitiveness compared to other technologies [80]. The company Lazard, described by Guimarães (2019) [81], a globally recognized financial consulting firm, indicated in its 2018 annual LCOE analysis a continuous reduction in electricity generation costs derived from alternative energy technologies, particularly solar and wind energy. In certain scenarios, the costs of alternative energy have decreased to the point of being equal to or below the marginal cost of conventional generation. These findings underscore the potential and economic efficiency of renewable energies in the global context, as well as the significant advancements in available renewable energy technologies.

4.4.3 Governmental incentives

It can be asserted that measures aimed at a country's energy and climate policy are regarded as catalysts for technological innovation. Thus, these measures can directly impact cost reductions, thereby generating incentives, that is, policies can enhance market deployment [78]. However, the slow progress in providing sufficient rural electricity has been attributed, in part, to the insistence on cost recovery, particularly when projects are financed by private institutions. Additionally, there is a failure to increase rural household incomes and to



efficiently design tariffs and adapt regulatory systems that could make electricity more accessible to poorer communities [82].

4.4.4 Macroeconomics

The economic analysis can be divided into two main aspects: macroeconomic sustainability and microeconomic sustainability [3,43]. The macroeconomic factor pertains to the contribution of energy modality to the overall economy by fostering new investments, ensuring access to energy at a reasonable cost, enhancing energy security, and developing infrastructure such as highways, power grids, and landfills.

Moreover, this aspect is related to energy security generation, as it increases network reliability and access to energy. According to Bölük and Mert, (2014) [83], projections indicate an annual growth of approximately 3% in the consumption of renewable energy for global electricity generation until 2035. These forecasts suggest a significant increase in the share of renewable energy, reaching 23% of electricity production by 2035, with notable emphasis on investments in wind and hydropower.

During the systematic literature review (SLR), particularly regarding countries in the European Union, it becomes evident that renewable energy policies tend to be more effective in promoting innovation in countries with more modern market structures. However, it is noteworthy that the increased competition in this sector can lead to the generation of low-quality energy modality patents, while environmental policies are crucial for the development of high-quality green patents [84].

4.4.5 Microeconomics

The microeconomic factor should encompass the costs associated with planning and utilizing the employed technology, as well as construction, operation, maintenance, investment internal rate of return, useful life, net present value, annual production, and unemployment rates. Policies that promote renewable energy typically envision long implementation timelines and are based on feed-in tariffs, auctions, and Net Metering.

Results from studies analyzing technology diffusion scenarios up to 2030 highlighted policy strategies aimed at advancing grid-connected photovoltaic generation [84,85]. The mechanisms examined include the Net Metering compensation scheme, Feed-in Tariffs, and direct subsidies for photovoltaic installations. The findings indicated that distributed photovoltaic generation technology presents promising opportunities for diversifying the energy matrix, offering potential economic and environmental benefits [84,86].

5. Importance of Key Factors

This chapter is divided into three sections. The first section presents a summary of the profile of experts who responded to the AHP weighting survey. The second section presents the results



obtained and a brief discussion on the weights. Finally, the third section outlines the perspectives shared by the respondents, which were gathered through open-ended discursive questions at the end of the questionnaire.

5.1 Expert Profile

The 29 experts interviewed predominantly hold engineering degrees, with Electrical Engineering (7), Civil Engineering (4), and Control and Automation Engineering (3) being the most common fields of study. Additionally, professionals with backgrounds in Architecture and Urban Planning were identified, along with postgraduate and doctoral degree holders in related fields.

Regarding professional occupation, most participants work directly in the energy sector, performing technical and strategic roles in companies and specialized institutions. A smaller portion is affiliated with academia, holding positions as professors and researchers at universities and research institutes. As illustrated in Figure 5, the professional occupations of the interviewed experts are presented.

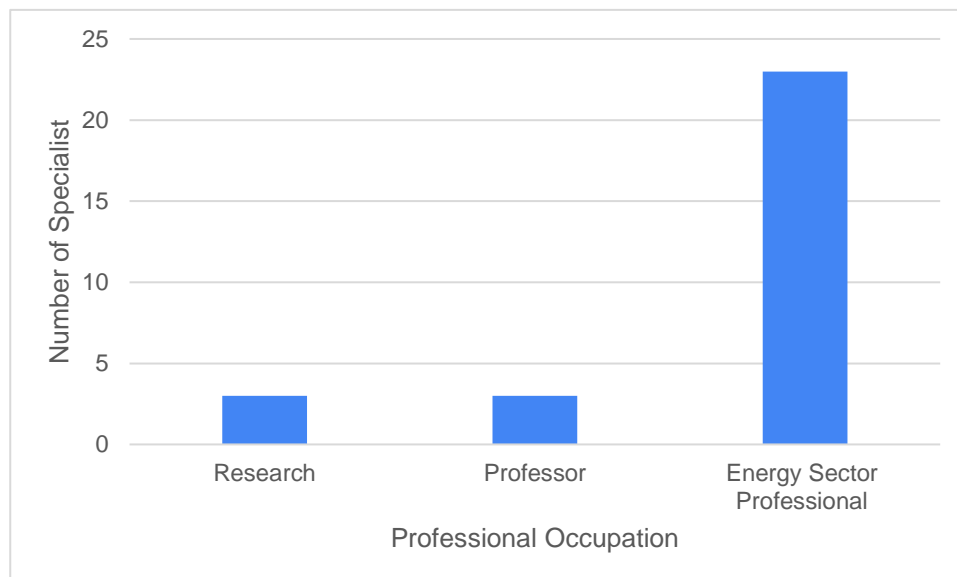


Figure 5. Professional Occupation of the Interviewed Expert.

The length of experience of the experts in the energy sector varies significantly, reflecting a diversity of backgrounds that enrich this research. The collected data show that a considerable portion of the respondents—15 in total—have between 6 to 10 years of experience in the field, while a significant group of 6 respondents have accumulated more than 20 years of expertise. This distribution suggests a balanced combination of professionals with well-established careers and those who bring innovative perspectives to the sector. These data can be observed



in Figure 6, presented below, which highlights the length of experience of the interviewed professionals.

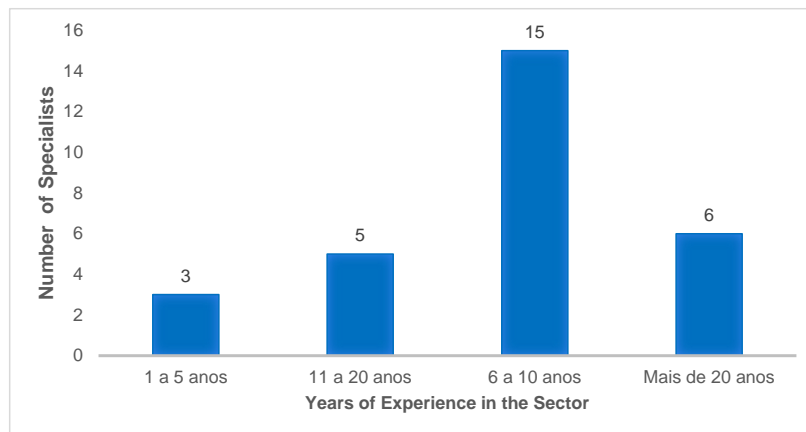


Figure 6. Years of Experience in the Sector of the Interviewed Experts.

The interviewed experts are distributed across various regions of Brazil, with a notable concentration in the states of Rio Grande do Sul, São Paulo, and Minas Gerais, as shown in Figure 7. This geographical diversity provides a comprehensive perspective on the challenges and opportunities within the energy sector across different regional contexts, considering factors such as infrastructure, public policies, and climatic conditions.

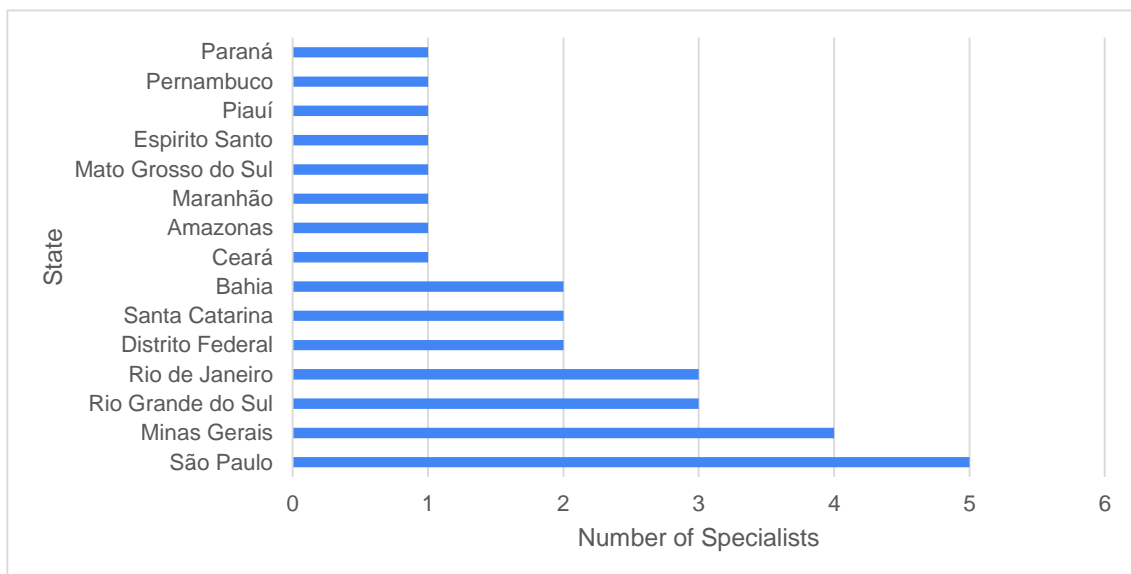


Figure 7. Distribution of Interviewed Specialists by State.

The age range analysis of the experts reveals an average age of approximately 40 years, with variations between younger participants and those with more extensive experience in the sector. Regarding gender distribution, there is a male predominance, with 25 male experts among the



respondents. However, the female participation of 4 interviewees, although lower, reflects the growing inclusion of women in the energy sector.

The profile of the interviewed experts highlights a diversity of academic backgrounds, professional experience, and geographic distribution, contributing to a multidisciplinary and comprehensive approach to the research. The combination of seasoned professionals and those with innovative perspectives enables a balanced analysis of the challenges and opportunities within the energy sector. These insights are crucial for contextualizing the opinions expressed throughout the study and strengthening the validity of the conclusions presented in the following chapters.

5.2 Weighting Results

This chapter presents a detailed analysis of the weights assigned to the dimensions and factors, accompanied by a critical evaluation of the patterns observed in the experts' opinions. Additionally, the implications of these results for the development and applicability of the framework in different rural contexts are discussed. The results of this stage are presented in Table 6.

Table 6. Weighting Results.

Dimensions	Global weight	Factors	Weight in the dimension
SOCIAL	23,70%	Impact on the Local Community	43.63%
		Social Equity	22.27%
		Education & Awareness	34.10%
ENVIRONMENTAL	29,97%	Emission Reduction	28.10%
		Impact on Biodiversity	29.12%
		Sustainable Resource Use	42.78%
TECHNICAL	18,07%	Technological Innovations	25.68%
		Energy Efficiency	33.01%
		Support Infrastructure	41.31%
ECONOMIC	27,52%	Implementation Cost	33.49%
		Economic Efficiency	27.26%
		Government Incentives	12.83%



		Macroeconomics	9.94%
		Microeconomics	13.46%
Average RC	24,82%	Average RC	19,68%
Standard Deviation RC	5,18%	Standard Deviation RC	2,48%

To ensure the consistency of judgments in the AHP method, the Consistency Ratio (CR) was calculated. CR is a key indicator within the AHP method, as it measures the reliability of comparisons made in the judgment matrix. For this study, a CR value below 25% was considered acceptable; values exceeding this threshold require a reassessment of comparisons. The average CR for the global weights was 24.82%, with a standard deviation of 5.18%, making it acceptable. At the factor level, the CR had an average value of 19.68% and a standard deviation of 2.48%, indicating a controlled variation in the distribution of weights.

Understanding that the implementation of renewable energy systems in rural areas can be structured into four dimensions—social, environmental, technical, and economic—each with specific weights in their evaluation. The environmental dimension, with a weight of 29.97%, focuses on emission reduction (28.1%) as a core strategy for mitigating climate change impacts. The impact on biodiversity (29.12%) is also assessed, considering the effects of energy technologies on local ecosystems. The most relevant factor within this dimension is sustainable resource use (42.77%), emphasizing efficiency in raw material consumption and the adoption of recycling practices.

The economic dimension, which represents 27.52% of the total evaluation, highlights implementation cost (33.49%) as its main concern, reflecting the budgetary challenges faced by rural properties. Economic efficiency (27.26%) is emphasized due to the need for return on investment and long-term financial viability. While government incentives (12.83%) play a significant role in enabling these solutions, direct impacts on microeconomics (13.46%) and macroeconomics (9.94%) also influence the adoption of sustainable technologies, underscoring the importance of public policies and strategic investments in the rural energy sector.

The social dimension, representing 23.7% of the total importance, highlights the impact on the local community (43.63%) as the most relevant factor, considering job creation and improved quality of life. Additionally, social equity (22.27%) emphasizes the need for inclusion and accessibility of energy solutions across different socioeconomic profiles. Another crucial aspect is education and awareness (34.1%), aimed at informing rural managers about the environmental and economic benefits of renewable energy, promoting a more informed and sustainable transition.



Finally, the technical dimension (18.07%) identifies support infrastructure (41.31%) as an essential element to ensure the longevity and functionality of energy systems. Energy efficiency (33.01%) emerges as a key factor in optimizing the utilization of available resources, while technological innovations (25.68%) play a crucial role in developing modern and sustainable solutions.

Adapting energy efficiency to distributed microgeneration stands out as a promising strategy to improve the rural energy sector. This approach not only promotes sustainability and self-sufficiency among producers but also enables the creation of smart microgrids composed of various energy generation modalities. These microgrids have the potential to significantly reduce production costs while creating new economic opportunities, such as land and equipment sharing, providing an additional source of income during seasonal periods.

The choice of energy generation type is intrinsically linked to the available grid infrastructure in the region. In areas lacking grid access or with transmission capacity limitations, the implementation of an isolated network—based on solar, hydro, or biomass energy—must be considered. Conversely, in locations with access to the distribution network, it is possible to opt for cogeneration systems or establish rural electrification cooperatives, promoting collective benefits and greater efficiency in energy resource utilization.

Two dimensions stand out: Environmental (29.97%) and Economic (27.52%). These reflect the experts' concerns regarding current rural issues in the country, where environmental and ecological footprints have become key research priorities.

5.3 Expert Opinions

The experts were invited to voluntarily answer three open-ended discussion questions, allowing them to share their opinions and experiences. The questions addressed ideal energy modalities, innovative energy technologies applicable to this study, and the development of a tool to assist in the selection and decision-making process for energy modality in rural areas.

During the interviews, several energy modalities were identified as relevant in the studied context. For example, photovoltaic solar energy is widely adopted in rural areas due to the abundance of solar radiation and the feasibility of decentralized installations. Advances in solar panel efficiency and energy storage solutions, such as lithium-ion batteries, make this technology even more viable and accessible for producers.

Another promising alternative mentioned is the use of agro-industrial waste for biomass and biogas generation. The conversion of organic waste into energy not only reduces environmental impacts but also enhances energy autonomy for rural properties. Additionally, this technology allows for the cogeneration of thermal and electrical energy, increasing system efficiency.



The utilization of water resources for energy generation is a viable solution in regions with adequate water availability. Small hydropower plants and micro-hydro systems present great potential, especially when integrated with smart grids, optimizing energy supply. Furthermore, although less commonly adopted in rural areas, wind energy can serve as a complementary solution in regions with favorable wind conditions. Small wind turbines can be combined with other energy sources, improving efficiency and stability in the electricity supply.

Some researchers emphasized that technological innovation plays a crucial role in the advancement and expansion of renewable energy in rural areas. Key innovations include: smart microgrids, integrating different energy sources and allowing efficient electricity distribution through sensor technology and automation; advancements in batteries and energy storage, improving flexibility in energy usage, ensuring supply even during low-generation periods; increased energy efficiency, measures such as LED lighting and high-efficiency motors help reduce waste and optimize consumption in rural activities.

Several interviewees pointed out that defining the ideal energy matrix for rural properties is challenging due to the variety of options and the complexity of energy systems. However, they emphasized that digital tools that assist in technical and economic analysis of energy projects are fundamental. The main criteria considered include:

- Cost-benefit analysis: evaluating initial investment and financial return;
- Ease of maintenance: selecting technologies with simplified operation;
- Socio-environmental impacts: reducing ecological footprint and improving quality of life.

From the analysis of the open-ended questionnaire responses, it is evident that renewable energy holds great potential to transform rural areas, providing energy autonomy and sustainability. The adoption of new technologies and decision-support tools is crucial to maximizing the benefits of these solutions, fostering more efficient and resilient rural development.

The interviewees in this study emphasized the need for tools that facilitate the selection of the optimal energy matrix, considering factors such as:

- Reduction of operational and maintenance costs;
- Ease of access and implementation in rural areas;
- Positive social and environmental impact;
- Overabundance of options in the market, complicating decision-making.



The transition to renewable energy sources in the rural sector is an expanding reality, and technical and technological support will be essential to ensure a sustainable and efficient future for rural communities.

6. Conclusion

The selection of suitable renewable energy sources for rural properties faces challenges related to technical, economic, and environmental feasibility. This article aimed to identify, map, and analyze studies on decision-making frameworks for renewable energy options in rural properties through a systematic literature review and bibliometric analysis. Based on these methods, it was possible to develop the dimensions and their respective factors to be studied, which were subsequently weighted according to the metrics of the Analytic Hierarchy Process (AHP) method, with the participation of 29 experts in the field.

The study highlights the importance of applying multi-criteria decision-making (MCDM) methods in selecting energy modalities for rural areas. These methods are essential for dealing with the complexity involved in comparing energy alternatives, considering economic, environmental, social, and technical dimensions. The ability of MCDM to adjust the weighting of criteria according to the specificities of each region enables more efficient decision-making, promoting both grid-connected (on-grid) and independent (off-grid) solutions, depending on the scenario.

The environmental dimension, which carries the highest weight compared to the others, demonstrated that the use of renewable sources can mitigate greenhouse gas emissions and preserve biodiversity, but it must be accompanied by sustainable resource utilization practices. The second highest relative weight, the economic dimension, revealed that implementation and operational costs, along with government incentives, are decisive factors for the feasibility of renewable energy solutions. The social dimension emphasized the role of community impact, job creation, and local acceptance—critical factors for the success of energy projects. Lastly, the technical dimension underscored the importance of technological maturity, energy efficiency, and the availability of support infrastructure.

The analysis revealed that achieving sustainable rural development requires an integrated consideration of these four dimensions, weighted accordingly. The energy transition in rural areas is not limited to economic and technological aspects but must also address social and environmental issues, promoting community inclusion and ensuring energy security.

Although MCDM cannot be considered a universally superior solution—since each method has advantages depending on the objectives and contexts of application—the results indicate that the pursuit of sustainability and energy independence is a recurring theme in the analyzed publications. This suggests the relevance of proposing combinations of energy systems. Among the most applied MCDM methods, the Analytic Hierarchy Process (AHP) stands out



for its simplicity, although techniques such as TOPSIS and PROMETHEE are also widely used. It was concluded that the application of these methods is essential not only to meet the immediate needs of rural communities but also to contribute to their long-term sustainable development.

Finally, the study suggests that future research should explore the adaptation and enhancement of these methodologies and emerging technologies to further optimize decision-making in different rural contexts, incorporating new criteria and providing metrics for measuring each addressed factor. Ultimately, this could establish a ranking of the identified energy modalities for the studied environment. Thus, developing a specific decision-support framework for rural properties can provide a valuable tool for decision-makers, assisting in the selection and implementation of renewable solutions that promote economic, environmental, and social sustainability. This approach is fundamental to ensuring the sustainable progress of rural communities and achieving energy conservation and emissions reduction targets.

7. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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