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Article

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Evaluation and Ranking of Energy Alternatives for Implementation in Different Geographic Scenarios using Decision Methods: Case Study of Colombia

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ABSTRACT

In this research, several crucial aspects have been explored in the evaluation and ranking of energy alternatives in Colombia using advanced decision methods such as TOPSIS and Diffuse TOPSIS. The study analyzed how these techniques allow to effectively compare different renewable energy sources in various regions of the country, highlighting the importance of considering multiple approaches due to the unique geographical and energy characteristics of each region. Specifically, five regions were evaluated: Caribbean 1 and 2, Pacific 1 and 2, Andean, Amazonian and Orinoquia, observing significant differences in the evaluation of technologies between the models. In the evaluation of energy sources for each region, the potential of photovoltaic solar energy in the Caribbean and Orinoquia regions was emphasized due to the high solar radiation, wind energy in the Caribbean and Pacific regions due to its strong winds, and biomass in the Amazon and Andean regions thanks to the abundance of organic resources. These technologies not only contribute to the reduction of carbon emissions and the diversification of the energy matrix, but also promote a just energy transition by generating employment and improving the quality of life in local communities. The TOPSIS method and its diffuse variant make it possible to weigh criteria with different degrees of importance and manage uncertainty in decision-making, resulting in more precise evaluations adapted to specific contexts. This type of research is vital for decision-making in the Colombian electricity sector, as it provides a solid and replicable methodology for evaluating energy alternatives in an integral way. The results not only contribute to environmental sustainability, but also boost the socio-economic development of the regions, fostering an equitable and fair energy transition.

Keywords: Energy Transition, Renewable Energies, Selection and Decision Criteria, Multi-objective Optimization
JEL Classifications: C44, C45, C46, C65

1. INTRODUCTION

The growing global demand for energy, combined with the prevailing need to address environmental challenges, has driven the transition to more sustainable and renewable energy sources. Colombia, in its commitment to climate change mitigation, has identified the significant potential of renewable energies distributed in its various geographical regions (Liu et al., 2023). However, the efficient management and optimal selection of these energy sources are presented as crucial challenges. In this context, the present research addresses the implementation of two innovative metaheuristic methods, TOPSIS and TOPSIS with fuzzy logic, for the weighting, hierarchization and improved selection of renewable energy sources in Colombia (Dias et al., 2022).

The transition to a more sustainable energy model stands as an imperative necessity in the global context. Colombia, a country characterized by its geographical diversity, is positioned as a favorable scenario for the exploration and exploitation of renewable energy sources (Nazim et al., 2022). The effective management of this natural wealth, however, becomes a complex and multidimensional task that requires advanced analytical approaches. In this scenario, the proposed research focuses on the implementation of two innovative metaheuristic methodologies: TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and TOPSIS with fuzzy logic (Rezaei, 2022). These methodologies, recognized for their ability to address complex decision-making problems, are configured as key tools in the weighting, hierarchization and selection of renewable energy sources in Colombia (Manuel Moreno Rocha et al., 2022).

On the one hand, TOPSIS, initially developed for decision-making in management and planning problems, stands out for its ability to evaluate alternatives in relation to multiple criteria (Pramanik et al., 2022). In the context of the selection of renewable energy sources, TOPSIS allows the systematic comparison of options, considering technical, economic and environmental aspects (Huang et al., 2023). By using this approach, the research seeks to overcome the limitations of conventional methods by offering a comprehensive and considered view of the different energy sources, taking into account their strengths and weaknesses in the specific context of each Colombian geographical region. While the inclusion of fuzzy logic in the TOPSIS method amplifies its ability to adapt to the complex and changing reality of renewable energy sources. The inherent variability of these sources, marked by climatic fluctuation and other external factors, introduces a component of uncertainty that needs to be addressed (Quynh, 2024). TOPSIS with fuzzy logic incorporates the necessary flexibility to handle imprecise or vague information, allowing a more robust and realistic evaluation of energy alternatives (Jain et al., 2024). Thus, the research seeks not only to identify the most optimal options under ideal conditions, but also to consider less predictable scenarios, increasing the adaptability of the model to changing environmental conditions (Jain et al., 2024). In a global context where environmental sustainability has become imperative, the careful selection of renewable energy sources acquires crucial relevance, the choice of the appropriate energy source for each region not only impacts on the efficiency and sustainability of energy supply, but also directly influences the reduction of greenhouse gas emissions and the preservation of local ecosystems (Carpitella et al., 2022). The efficient implementation of renewable energies represents not only an environmentally conscious strategy, but also an opportunity for economic and social development at the regional level (Baydaş et al., 2024). In this context, the proposed research not only seeks to offer technical solutions, but also to establish a comprehensive framework that addresses the strategic importance of the selection of renewable energy sources in the sustainable development of Colombia (Eguiarte et al., 2022).

At the international level, the selection of renewable energy sources has become a crucial issue on the global sustainability agenda, various countries have adopted strategies to diversify their energy matrices, prioritizing the transition to cleaner and more sustainable resources (Wang et al., 2024). The implementation of decision methods, such as TOPSIS and its variant with fuzzy logic, has gained prominence in this context (Pechsiri et al., 2023). The ability to evaluate multiple criteria and consider the uncertainty associated with renewable sources has proven to be essential in decision-making at the international level, where conditions and variables can vary significantly between regions (Shao et al., 2023).

In the Latin American region, geographical and climatic diversity presents unique challenges and opportunities in the selection of renewable energy sources. Countries such as Brazil, Chile and Mexico have led the implementation of renewable technologies, recognizing the importance of maximizing the potential of their natural resources (Turoń, 2022). The application of metaheuristic methods in energy decision making is aligned with the need to consider climate variability and geographical complexity (Diviya et al., 2024). The adaptation of approaches such as TOPSIS to the specific conditions of Latin America contributes to a more efficient and sustainable transition towards renewable energy sources in the region. Colombia, immersed in a rich geographical diversity, faces particular challenges in the selection of renewable energy sources (Zhou et al., 2024). The implementation of decision methods becomes essential to weigh local factors, considering variables such as altitude, climate, and the specific topography of each region (Manuel Moreno Rocha et al., 2022). The TOPSIS methodology, with its ability to evaluate alternatives based on multiple criteria, is presented as an especially valuable tool in this context (Pazouki et al., 2022). The application of fuzzy logic in the TOPSIS variant, on the other hand, allows adapting to the uncertainty inherent to the changing conditions of the Colombian environment, ensuring informed and strategic decisions in the implementation of renewable energies at the local level (Sithara et al., 2022). International cooperation in the implementation of decision methods for the selection of renewable energy sources is presented as an essential catalyst to boost global sustainability, the exchange of best practices between countries, the standardization of analytical approaches and collaboration in advanced research contribute to a collective progress towards more sustainable energy matrices (Hegde et al., 2024). The application of metaheuristic methods not only strengthens decision-making capacity at the local, regional and international levels, but also establishes a framework for continuous innovation and adaptability as environmental and technological conditions evolve (Zhou et al., 2024). In this context, the research and application of methodologies such as TOPSIS and TOPSIS with fuzzy logic become key elements to promote efficiency and sustainability in the selection of renewable energy sources at different geographical scales (Manuel Moreno Rocha et al., 2022).

In this context, the essential question arises: How can Colombia optimize the weighting, ranking and selection of renewable energy sources in its different geographical regions to maximize energy efficiency and minimize environmental impact? This central issue triggers the need to investigate and develop innovative and efficient approaches that allow informed and strategic decision-making in the transition to a more sustainable and diversified energy matrix.

A peculiarity of this research is that only national (Colombian) experts were used, this in order that in future research an analysis is carried out on the final results of the implementation of the methodologies, in such a way that it is possible to find the existence or non-existence of a relationship between the findings obtained, for each of the methods. It must be clear and precise that the results of any decision method do not correspond to an absolute truth, these results correspond to an answer of a group of experts, to a weighting of some previous method or simply a numerical value for some criterion or sub-criterion dependent on variable conditions, as happens in this research, the Initial investment USD/MWh criterion, is a variable value, which adjusts to market conditions, for this research the criteria Environmental impact, Analysis of infrastructure in installation, operation, etc and Conflicts with other economic actors, correspond to values obtained from an arithmetic mean of a survey conducted to a group of Colombian experts. For the selection of the experts in this research, their years of expertise, the products and research topics published that will be related to the topic of this research, proven experience in the commercial or industrial sector associated with the electricity sector were evaluated.

The relevance of this research lies in its ability to address not only Colombia's immediate energy demands, but also in its ability to establish a solid and replicable methodological framework. The application of metaheuristic methods such as TOPSIS and TOPSIS with fuzzy logic is presented as a promising strategy to overcome the limitations of conventional approaches, considering the complexity and uncertainty inherent in the evaluation of renewable energy sources. By achieving a more precise weighting and hierarchization, this study will significantly contribute to strategic decision-making in the implementation of sustainable energy solutions in Colombia, serving as a valuable model for other countries with similar challenges.

2. MATERIALS AND METHODS

The methodology section of this article deploys a meticulous and rigorous approach to address the particular challenges associated with the evaluation of renewable energy sources in Colombia. The implementation of metaheuristic methods, specifically TOPSIS and TOPSIS with fuzzy logic, constitutes the backbone of our methodological strategy. These approaches were carefully selected due to their demonstrated ability to deal with the complexity inherent in decision-making in a changing and diverse environment such as Colombia's (Kaya et al., 2022). The choice of TOPSIS and fuzzy logic TOPSIS as metaheuristic methods is the result of a careful assessment of their suitability to address the variables and uncertainty associated with the selection of renewable energy sources. TOPSIS, with its ability to handle multiple criteria and provide trade-offs, offers a robust basis for the weighting and prioritization of energy options (Mandal et al., 2024). On the other hand, the integration of fuzzy logic into TOPSIS is justified by its ability to model the imprecision inherent in the variability of renewable energy sources, ensuring a more realistic and adaptive approach (Zhang et al., 2022).

The methodology developed takes into account the geographical diversity of Colombia, characterized by variations in altitude, climates and topographies (Rocha et al., 2024). The application of these methods is tailored to the particularities of each region, recognizing that there is no single approach that can encompass the complexity of the country's geographical conditions. The adaptability of TOPSIS and TOPSIS with fuzzy logic is presented as an essential element to ensure that renewable energy decisions are contextually relevant and strategically informed (Moreno et al., 2022). The methodology section details the key stages of implementation, from data collection to final evaluation, specific criteria, such as the availability of natural resources, environmental impact, and economic viability, are included to ensure a holistic assessment of each renewable energy source. In addition, sensitivity analyses are integrated to assess the robustness of the results against possible changes in environmental or technological conditions (Peters et al., 2022). The validation of the results obtained by applying TOPSIS and TOPSIS with fuzzy logic is done through comparisons with conventional approaches and review by experts in the field (Wang and Zhao, 2024). This validation process ensures the reliability and practical applicability of the results, strengthening the contribution of this research to the emerging field of efficient renewable energy management in Colombia (Moreno et al., 2022).

2.1. Variables Taken into Account

The strategic selection of renewable energy alternatives in countries such as Colombia represents a multifaceted challenge, where the application of metaheuristic methods, particularly TOPSIS, is presented as a fundamental tool. In this context, the consideration of key criteria is of crucial importance. This text addresses the relevance of three essential criteria: the Initial Investment in USD/MWh, the Environmental Impact and the Infrastructure Analysis. In addition, it explores the need to evaluate conflicts with other economic actors, highlighting the interconnection of these factors in strategic decision-making for sustainable development.

- Initial investment in USD/MWh: Economic rationale

The criterion of Initial Investment in USD/MWh stands as a fundamental pillar in decision-making related to renewable energies. The economic efficiency of an energy alternative depends not only on its environmental performance, but also on the relationship between the initial investment and energy production over time (Zhang et al., 2024). Assessing this criterion provides a clear view of the long-term financial viability of renewable options, enabling planners and decision-makers to direct resources towards economically sustainable solutions that drive the energy transition (Manuel Moreno Rocha et al., 2022).

- Environmental impact: Long-term sustainability

Consideration of Environmental Impact stands as a moral and practical imperative in the choice of renewable energy sources. Measuring an alternative's environmental impact is not limited to its greenhouse gas emissions (Tobajas et al., 2022); It must cover the entire life cycle, from production to decommissioning (Wang et al., 2024). Evaluating this criterion ensures the selection of options that not only reduce emissions, but also minimize other adverse impacts on local and global ecosystems, ensuring a sustainable future for generations to come (Manuel Moreno Rocha et al., 2022).

- Infrastructure analysis: Operational efficiency and successful deployment

The Infrastructure Analysis criterion is presented as a key determinant for the successful deployment of renewable energy projects. Planning and implementing efficient and adequate infrastructures are essential to ensure optimal operation over time (Işık et al., 2024). Factors such as geographic location, transmission capacity, and grid connectivity are crucial elements to evaluate. The consideration of this criterion in the selection phase makes it possible to anticipate possible operational challenges and optimize the efficiency of the infrastructure, ensuring the long-term success of the renewable initiative (Manuel Moreno Rocha et al., 2022).

- Conflicts with other economic actors: Sustainable integration into the social and economic environment

The assessment of Conflicts with Other Economic Actors highlights the need to consider the dynamics and relationships in the social and economic environment. In a country like Colombia, where the diversity of economic actors is remarkable, the identification and mitigation of potential conflicts becomes a critical factor. The sustainable integration of renewable energy alternatives requires careful analysis of potential tensions with local communities, existing industries, and other economic actors (Priyanto et al., 2024). Assessing this criterion ensures an energy transition that is not only technically feasible but also socially and economically inclusive (Manuel Moreno Rocha et al., 2024). Taken together, these criteria not only provide a holistic framework for the assessment of renewable energy options, but also underscore the need for a balanced approach that considers economic, environmental and social aspects (Wang et al., 2024). The application of metaheuristic methods such as TOPSIS enhances this comprehensive assessment, enabling informed decisions that drive sustainability and sustainable development in Colombia's energy landscape (Manuel Moreno Rocha and Jotty, 2022).

One of the variables to be taken into account in the implementation of the TOPSIS methodology was the price of the 1 MW/h installation, according to the bibliography consulted, the prices according to the technology to be implemented oscillate as follows:

- Solar photovoltaic: According to the International Renewable Energy Agency's (IRENA) "Renewable Power Generation Costs in 2022" report, the levelized cost of utility-scale solar PV generation is in the range of \$0.03-\$0.05 per kWh, which equates to approximately \$30-\$50 per MWh (Executive, n.d.; Transition, n.d.). This translates to approximately \$30-\$50 per kW/h (Pechsiri et al., 2023).
- Offshore wind: According to the same IRENA report, the levelized cost of offshore wind power generation is in a range of \$0.06-\$0.11 per kWh, or around \$60-\$110 per MWh. This equates to approximately \$60-\$110 per kW/h1 (Lechón et al., 2023).
- Onshore wind: IRENA's "Renewable Power Generation Costs in 2022" report indicates that the levelized cost of onshore wind power generation is between \$0.04 and \$0.08 per kWh, equivalent to approximately \$40-\$80 per MWh (Transition, n.d.). This translates to approximately \$40-\$80 per kW/h1 (Ceballos-Santos et al., 2023).
- Biomass: According to IRENA's "Renewable Power Generation Costs in 2022" report, the levelized cost of power generation from biomass is in a range of \$0.05-\$0.13 per kWh, which equates to approximately \$50-\$130 per MWh. This translates to approximately \$50-\$130 per kW/h1.
- Tidal: \$403 per MW/h (IRENA, 2019).
- Wave: \$600 per MW/h (IRENA, 2019)
- Small-scale hydropower: IRENA's "Renewable Power Generation Costs in 2022" report shows that the levelized cost of small-scale hydropower generation is in a range of \$0.03-\$0.05 per kWh, or around \$30-\$50 per MWh (Executive, n.d.). This equates to approximately \$30-\$50 per kW/h1.
- Large-scale hydropower: According to the same IRENA report, the levelized cost of large-scale hydropower generation is in the range of \$0.01-\$0.03 per kWh, which equates to approximately \$10-\$30 per MWh. This translates to approximately \$10-\$30 per kW/h1 (Transición, n.d.).
- Geothermal: According to IRENA's "Renewable Power Generation Costs in 2022" report, the levelized cost of geothermal power generation is in a range of \$0.04-\$0.09 per kWh, or around \$40-\$90 per MWh. This equates to approximately \$40-\$90 per kW/h1 (Ejecutivo, n.d.).

2.2. Topsis Methodology

The implementation of the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) involves a series of systematic steps designed to evaluate and rank alternatives based on multiple criteria. The following are the key steps to apply the TOPSIS method effectively:

1. Identification of the Problem and Definition of Criteria and Alternatives: The first step is to clearly define the decision problem and determine the criteria that will be used to evaluate the alternatives. These criteria should be relevant and measurable. Also, the alternatives that will be evaluated must be identified.
2. Construction of the Decision Matrix: A decision matrix is created where the rows represent the alternatives and the columns represent the criteria. The elements of the matrix are the values that indicate the performance of each alternative with respect to each criterion.
3. Normalization of the Decision Matrix: Because the criteria may have different units of measurement, it is necessary to normalize the values of the decision matrix to make them comparable. This is done using the normalization formula:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x^2_{kj}}} \quad (1)$$

where r_{ij} is the normalized value, x_{ij} is the original value, and m is the number of alternatives.

4. Construction of the Normalized Weighted Matrix: The normalized values are multiplied by the corresponding weights of the criteria to obtain the normalized weighted matrix. The weights reflect the relative importance of each criterion and must be determined in advance.

$$v_{ij} = w_j \, r_{ij} \quad (2)$$

where v_{ij} is the normalized weighted value and w_j is the weight of the criterion j.

5. Determination of Ideal and Anti-Ideal Solutions: The positive ideal (best value for each criterion) and negative ideal (worst value for each criterion) solutions are identified.

$$A+ = \{\max (v_{ij}) \mid j \in J\}, \{\min (v_{ij}) \mid j \in J'\} \quad (3)$$

$$A- = \{\min (v_{ij}) \mid j \in J\}, \{\max (v_{ij}) \mid j \in J'\} \quad (4)$$

where j J is the set of criteria to be maximized and j "J" is the set of criteria to be minimized.

6. Calculation of the Distances to the Ideal Solutions: The Euclidean distance of each alternative to the positive and negative ideal solutions is calculated.

$$Di+ \ = \sqrt{\sum_{j=1}^{n} v_{ij} + A_j^{+2}} \quad (5)$$

$$Di- \ = \sqrt{\sum_{j=1}^{n} v_{ij} - A_j^{-2}} \quad (6)$$

where Di+ is the distance to the positive ideal solution and Di- is the distance to the negative ideal solution.

7. Calculation of the Similarity Coefficient to the Ideal Solution: The similarity coefficient is determined for each alternative, which indicates how close each alternative is to the positive ideal solution.

$$Ci* = \frac{D_i^-}{D_i^+ + D_i^-} \quad (7)$$

where $Ci*$ varies between 0 and 1, 1 being the positive ideal solution.

8. Ranking of Alternatives: Alternatives are ranked according to their similarity coefficients $Ci*$. The alternative with the highest coefficient is considered the best option.

2.3. Fuzzy Set Theory

2.3.1. Fundamental definitions

A fuzzy set over the universal set is defined as: $\tilde{F}G$

$$\tilde{F} = \{g, \mu_{\tilde{F}}(g) \mid g \epsilon G\} \quad (8)$$

Where represents the degree of membership of element $\mu_{\tilde{F}}(g): G[0,1]g$. To $\tilde{F}$ such that for all FST allows partial membership of an element in a set. The element belongs completely to, if the degree of membership value equals one. On the other hand, the degree of membership value of is zero, if it does not belong to the set. The element is a partial membership of the fuzzy set, if the degree of membership is between 0 and 1: Different types of fuzzy numbers have been used for modeling the linguistic variables like triangular fuzzy numbers (TFNs), trapezoidal fuzzy numbers, Gaussian fuzzy numbers, Bell shaped fuzzy numbers etc. $\mu_{\tilde{F}}(g) \epsilon [0,1] g \epsilon G g \tilde{F} g g \tilde{F} g \tilde{F}$ (Liang et al., 2022). Among these numbers, we have used TFNs because of its simplicity in understanding and representing the decision makers linguistic information (Rezaei, 2022).

A TFN is a normal, convex fuzzy subset of, with a piece wise linear relationship function, defined by $\widetilde{F} = (c, p, d) G \mu_{\tilde{F}}$ (Pramanik et al., 2022).

$$\mu_{\tilde{F}}(S) = \begin{cases} 0\, for g < c, \\ \dfrac{g-c}{p-c}\, for c \le g \le p, \\ \dfrac{d-g}{d-p}\, for p \le g \le d, \\ 0\, for g > d \end{cases} \quad (9)$$

In wich and are real numbers with. Let and be TFNs. $c, pdc < p < d \widetilde{E} = (c_1, p_1, d_1) \widetilde{F} = (c_2, p_2, d_2)$

Then, (a) Addition:

$$\widetilde{F}(+)\widetilde{E} = (c_1 + c_2, p_1 + p_2, d_1 + d_2) c_1 \ge 0, c_2 \ge 0 \quad (10)$$

(b) Multiplication:

$$\widetilde{F}(\times)\widetilde{E} = (c_1 \times c_2, p_1 \times p_2, d_1 \times d_2) c_1 \ge 0, c_2 \ge 0 \quad (11)$$

(c) Subtraction:

$$\widetilde{F}(-)\widetilde{E} = (c_1 - c_2, p_1 - p_2, d_1 - d_2) c_1 \ge 0, c_2 \ge 0 \quad (12)$$

(d) Division:

$$\widetilde{F}(\widetilde{A}.)\widetilde{E} = (c_1 \widetilde{A}.d_2, p_1 \widetilde{A}.p_2, d_1 \widetilde{A}.c_2) c_1 \ge 0, c_2 \ge 0 \quad (13)$$

(e) Inverse:

$$\widetilde{E}^{-1} = \left(\frac{1}{d_1}, \frac{1}{p_1}, \frac{1}{c_1}\right) \ge 0 \quad (14)$$

2.4. Fuzzy Topsis

The Fuzzy TOPSIS method was proposed by Chen to solve the MCDM problems under uncertainty. Linguistic variables are used by the decision makers, to evaluate the weights of the NFRs and the ranking of the FRs. The weights of the NFR is represented by and it is given by the decision maker $M = (i = 1, \cdots, r) b^{th} D_b = (b = 1, \cdots, p) \tilde{Y}_i^b i^{th}$ (Zhou et al., 2024). The rating of the, is represented by with respect to NFR b and it specified by decision maker. This method includes the following steps $a^{th} FRFR_a = (a = 1, \cdots, q) \tilde{S}_{ab}^i i^{th}$ (Nesticò et al., 2022):

i. Aggregate the weights of NFRs and ratings of FRs specified by decision makers, as expressed in Eqs. (15) and (16) respectively r (Wang et al., 2024):

$$\tilde{y}_b = \frac{1}{r}\left[\tilde{y}_b^1 + \tilde{y}_b^2 + \cdots + \tilde{y}_b^r\right] \quad (15)$$

$$\tilde{s}_{ab} = \frac{1}{r}\left[\tilde{s}_{ab}^1 + \tilde{s}_{ab}^i + \cdots + \tilde{y}_{ab}^r\right] \quad (16)$$

ii. Construct the fuzzy decision matrix (FDM) of the FRs ($\widetilde{M}$) and the NFR, according to Eqs. (17) and (18): $(\widetilde{Y})D_1D_2D_bD_p$

$$\widetilde{M} = \begin{array}{c} FR_1 \\ FR_a \\ FR_q \end{array} \begin{bmatrix} \tilde{s}_{11} & \tilde{s}_{12} & \tilde{s}_{1b} & \tilde{s}_{1p} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{s}_{q1} & \tilde{s}_{q2} & \tilde{s}_{qb} & \tilde{s}_{qp} \end{bmatrix} \tag{17}$$

$$\tilde{Y} = \left[\tilde{y}_1 + \tilde{y}_2 + \cdots + \tilde{y}_p \right] \tag{18}$$

iii. Normalize the FDM of FRs using linear scale transformation. The normalized FDM is given by: $(\widetilde{M})\tilde{I}$

$$\tilde{I} = \left[\tilde{i}_{ab} \right]_{p \times q} \tag{19}$$

$$\tilde{i}_{ab} = \left(\frac{\tilde{c}_{ab}}{\tilde{d}_b^+}, \frac{\tilde{p}_{ab}}{\tilde{d}_b^+}, \frac{\tilde{d}_{ab}}{\tilde{d}_b^+} \right) \tag{20}$$

And (benefit criteria) (19). $\tilde{d}_b^+ = max_a \tilde{d}_{ab}$

$$\tilde{i}_{ab} = \left(\frac{\tilde{c}_b^-}{\tilde{d}_{ab}}, \frac{\tilde{c}_b^-}{\tilde{p}_{ab}}, \frac{\tilde{c}_b^-}{\tilde{c}_{ab}} \right) \tag{21}$$

And (cost criteria) (21). $\tilde{c}_b^- = max_a \tilde{c}_{ab}$

iv. Compute the weighted normalized FDM, by multiplying the weights of NFRs, by the elements of the normalized FDM $\widetilde{W}\, \tilde{y}_b \tilde{i}_{ab}$ (Rajagopal Reddy et al., 2023).

$$\widetilde{W} = \left[\tilde{w}_{ab} \right]_{p \times q} \tag{22}$$

where $\tilde{w}_{ab}$ is given by Eq. (23).

$$\tilde{w}_{ab} = \tilde{s}_{ab \times} \tilde{y}_b \tag{23}$$

v. Define the Fuzzy Positive Ideal Solution (FPIS) and the Fuzzy Negative Ideal Solution (FNIS), as: F^+ F^-

$$F^+ = \tilde{w}_1^+, \tilde{w}_b^+, \cdots, \tilde{w}_p^+ \tag{24}$$

$$F^- = \tilde{w}_1^-, \tilde{w}_b^-, \cdots, \tilde{w}_p^- \tag{25}$$

vi. Compute the distances and of each FR using the following Eqs: $m_b^+ m_b^-$

$$m_a^+ = \sum\nolimits_{b=1}^{q} m_w \left(\tilde{w}_{ab}, \tilde{w}_b^+ \right) \tag{26}$$

$$m_a^- = \sum\nolimits_{b=1}^{q} m_w \left(\tilde{w}_{ab}, \tilde{w}_b^- \right) \tag{27}$$

Where represents the distance between two fuzzy numbers. The vertex method is used to compute the distance between two fuzzy numbers m (···) (Khan et al., 2022):

$$m\left(\tilde{s}, \tilde{\tilde{u}}\right) = \sqrt{\frac{1}{3}\left[\left(c_s - c_u\right)^2 + \backslash\left(p_s - p_u\right)^2 + \left(d_s - d_u\right)^2 \right]} \tag{28}$$

vii. The ranking order of the FRs are determined by the closeness coefficient value. The is computed as: ($clos\_coff_a$) $clos\_coff_a$

$$clos\_coff_a = \frac{m_a^-}{m_a^+ + m_a^-} \tag{29}$$

The best FR is nearby to the FPIS and furthest to the FNIS.

For the evaluation of the variables or criteria that were used in this research such as; the environmental impact, the analysis of the structure in installation and the operation, finally the possible conflicts with other economic actors, a Likert scale structure was used, where the experts consulted should give their appreciation or degree of importance according to their experience and knowledge, the nomenclatures used are seen in Table 1 (Rezaei, 2022).

Before carrying out the implementation of the TOPSIS and TOPSIS DIFFUSE methods, the selected criteria were weighted and ranked (Diviya et al., 2024). To carry out this process, the application of the hierarchical analytical method (AHP) was chosen, a methodology widely supported and used by the research community. The results of this phase are presented in detail in Table 2, providing a clear overview of the relative importance of each criterion in the context of the selection of renewable energy sources (Dias et al., 2022). Table 2 not only reflects the aggregate results of the AHP process, but also provides a concrete example of the completion carried out by one of the 35 experts consulted in this research. The participation of experts in the field significantly enriches the weighting process, bringing specialized perspectives and practical experiences. It should be noted that, although a total of 35 people were consulted, only the responses of 28 experts in the AHP and TOPSIS methodologies were considered. This selection criterion was based on statistical rigor, excluding responses that did not meet the minimum values required for the radius and consistency index, thus guaranteeing the integrity and reliability of the data used in the development of subsequent methodologies.

2.4.1. Calculate normalised matrix and calculate weighted normalised matrix

The first fundamental step in the TOPSIS methodology is the calculation of the Normalized Matrix, Table 3, where each value in the original matrix is divided by the square root of the sum of the squares of the values in the same column (Savkovic et al., 2022). This normalizes the data, ensuring that all variables have the same relative scale (Chen and An, 2024). Subsequently, in the Weighted Normalized Matrix step, Table 4, the normalized values are multiplied by the weights assigned to each criterion. This weighting reflects the relative importance of each criterion in decision-making, allowing for a more accurate and contextualized evaluation of the alternatives (Alghassab, 2024).

Table 1: Implemented likert scale

1	Very Low
3	Low
5	Average
7	High
9	Very High

Table 2: Sample survey completed by expert

Alternatives	Initial investment USD/MWh	Environmental impact	Analysis of infrastructure in installation, operation, etc	Conflicts with other economic actors
Weightage	0.35	0.25	0.25	0.15
PV (Community energy/solar farms)	67	7	3	3
Wind (onshore/offshore)	96.75	9	3	3
Biomass	55	3	7	5
Tidal	403	5	9	5
Wave	600	5	9	5
Hydroelectric (small-scale)	62	3	3	3

Table 3: Calculate normalised matrix

Alternatives	Initial Investment	Environmental impact	Analysis of infrastructure in installation, operation, etc.	Conflicts with other economic actors
PV (Community energy/solar farms)	0.0909	0.4974	0.1944	0.2970
Wind (onshore/offshore)	0.1312	0.6396	0.1944	0.2970
Biomass	0.0746	0.2132	0.4537	0.4950
Tidal	0.5468	0.3553	0.5833	0.4950
Wave	0.8141	0.3553	0.5833	0.4950
Hydroelectric (small-scale)	0.0841	0.2132	0.1944	0.2970

Table 4: Calculate weighted normalised matrix

Alternatives	Initial Investment	Environmental impact	Analysis of infrastructure in installation, operation, etc.	Conflicts with other economic actors
PV (Community energy/solar farms)	0.0318	0.1243	0.0486	0.0445
Wind (onshore/offshore)	0.0459	0.1599	0.0486	0.0445
Biomass	0.0261	0.0533	0.1134	0.0742
Tidal	0.1913	0.0888	0.1458	0.0742
Wave	0.2849	0.0888	0.1458	0.0742
Hydroelectric (small-scale)	0.0294	0.0533	0.0486	0.0445

2.4.2. Calculate the ideal best and ideal worst value

Determining the Best Ideal Value and the Worst Ideal Value, Table 5, is essential for establishing extreme benchmarks in decision-making. In this step, you identify the alternatives that maximize and minimize each criterion, respectively (Adeel et al., 2022). The Best Ideal Value represents the ideal combination of criteria, while the Worst Ideal Value points to alternatives that meet the criteria poorly (Zhang et al., 2024). These extreme values serve as benchmarks to assess how close or far the alternatives are from the ideals, facilitating the final ranking (Li et al., 2023).

Table 5: Calculate the ideal best and ideal worst value

V+	0.0261	0.0533	0.0486	0.0445
V-	0.2849	0.1599	0.1458	0.0742

Table 6: Calculate the euclidean distance

Yes+	Yes-
0.0713	0.2751
0.1084	0.2597
0.0713	0.2818
0.1973	0.1175
0.2803	0.0711
0.2949	0.0898

2.4.3. Calculate the euclidean distance from the ideal best and calculate the euclidean distance from the ideal worst

Euclidean Distance, Table 6, is a key measurement in TOPSIS, as it quantifies the relative proximity of each alternative to the ideal values. Calculating the Euclidean Distance from the Best Ideal involves determining the Euclidean distance between each alternative and the Best Ideal Value (Zhou et al., 2024). Similarly, the calculation from the Worst Ideal measures the Euclidean distance from the Worst Ideal Value. These distances provide a quantitative assessment of how close or far each alternative is from the extreme values, contributing to informed decision-making (Eguiarte et al., 2022).

2.4.4. Calculate performance score

The last step in the TOPSIS methodology involves the calculation of the Performance Score for each alternative. This score is determined by dividing the Euclidean Distance from the Worst Ideal by the sum of the Euclidean Distance from the Best Ideal and the Euclidean Distance from the Worst Ideal (Fan et al., 2023). The Performance Score, which varies between 0 and 1, indicates the relative efficiency of each alternative relative to the ideals. A score closer to 1 reflects higher efficiency, while a score closer to 0 indicates lower efficiency (Wang and Zhao, 2024). This last step culminates in the final classification of the alternatives, facilitating the identification of the optimal option based on the established criteria (Cantillo et al., 2023), Table 7.

3. RESULTS

The results of this research have been organized in such a way that it is easy for the reader to understand them, the results have been grouped taking into account the geographical region taken, the evaluated alternatives and the decision method made, being so that for Figure 1, the weighting of energy alternatives for the Orinoquia region is observed, it is highlighted that for this area of Colombia according to the TOPSIS method, the three energy sources to be taken into account are PV, Biomass and Wind, with 51%, 39% and 7% respectively, while according to the TOPSIS-DIFUSSE methodology the alternatives to be considered to supply the demand of this area are the same ones obtained in TOPSIS, only now their percentages of importance differ, this time with 48%, 23% and 17%, respectively. The Orinoquía region, with its vast plains and natural resources, is crucial for Colombia's energy diversification. Geographically, it is made up of extensive plains and important rivers. Economically, it is noted for livestock farming, agriculture (rice and oil palm) and oil production. Climatically, it has a tropical savanna climate, with well-defined wet and dry seasons, as a conclusion Solar Photovoltaics is the most suitable option for the Orinoquía region, due to its wide plains and high solar exposure. These differences in the weighting weights, but equality in the hierarchization, only reflects the discrepancies that can be obtained when implementing decision methodologies.

The vast and lush Amazon region presents unique challenges and opportunities for the implementation of sustainable energy technologies. Geographically, it is composed of extensive tropical rainforests and flowing rivers. Economically, it focuses on subsistence agriculture, and the extraction of rubber and wood, climatically, it has a tropical humid climate, with constant rains, in Figure 2 the result of the categorization of energy sources for said region is evidenced as it happened with the Orinoquia region, the hierarchizations of the three main sources are the same for both methodologies, only varying the weightings of each of them, as it is observed in Figure 2 the results for the TOPSIS methodology were Biomass, PV, and Wind, with a value of 45%, 41% and 8% respectively, while for TOPSIS DIFUSSE, the values were 43%, 39% and 12% respectively.

The Andean region, with its varied topography and climate, is fundamental for the development of renewable energies in Colombia. Geographically, it is characterized by its mountain ranges, high altitudes and inter-Andean valleys. Economically, it is an agricultural region (famous for coffee and flowers), industrial and commercial. Climatically, it varies from temperate to cold, depending on the altitude, it is in this region where the largest energy generation of the entire Colombian territory is concentrated to date. In this region, if there was a discrepancy in the hierarchizations and in the weightings of the alternatives according to the implemented methodologies, in the case of TOPSIS, the hierarchization was large-scale hydroelectric, PV solar photovoltaic and small-scale hydroelectric with values of 53%, 29% and 9% respectively, while for the TOPSIS-DIFUSSE methodology the hierarchization was, large-scale hydroelectric, small-scale hydroelectric and solar photovoltaic, with values of 47%, 25% and 12% respectively, see Figure 3.

In the Pacific region, two scenarios "pacific 1" were evaluated where wind energy technology was not discriminated, while "pacific 2" discriminated between Offshore Wind and Onshore Wind. This region, with its dense tropical rainforest and abundant biodiversity, offers a particular scenario for the implementation of renewable energy technologies. Geographically, the region is composed of dense jungles and mountainous areas. Economically, it is based on fishing, gold and platinum mining, and subsistence agriculture. Climatically, it has a humid tropical climate, with a high amount of annual rainfall. For Figure 4 where the most relevant energy sources for this research were weighted and ranked, it happens that the rankings were the same, where solar photovoltaic, Offshore Wind and Onshore Wind are the three most relevant energy sources to be used in any of the implemented methods. On the other hand, in Figure 5, the three most relevant alternatives for this area were solar photovoltaic, wind and Biomass, the hierarchizations of alternatives are the same for any of the implemented methods.

Table 7: Calculate performance score

Pi	Rank	RANK%
0.7942	2	25.56
0.7055	3	22.71
0.7981	1	25.69
0.3733	4	12.02
0.2022	6	6.51
0.2333	5	7.51

Figure 1: Weighting of alternatives region Orinoquia

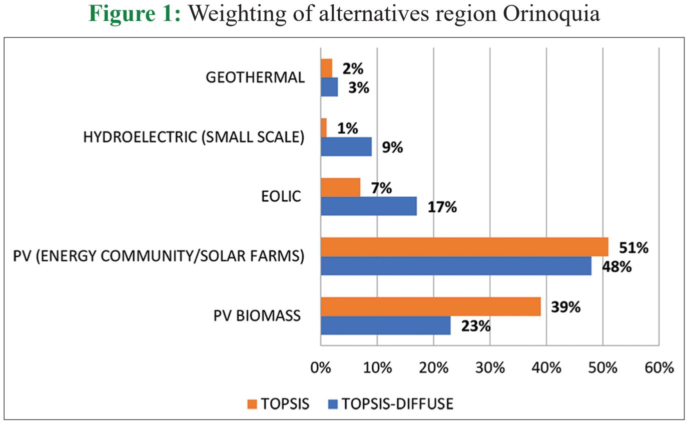


Figure 2: Weighting of alternatives Amazon region

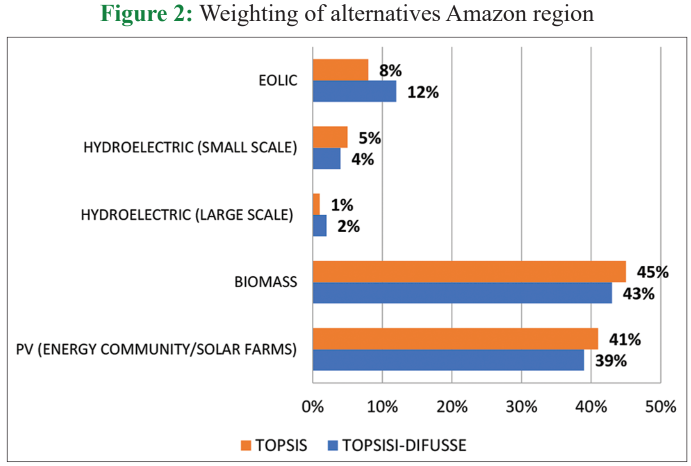


Figure 3: Weighting of alternatives Andean region

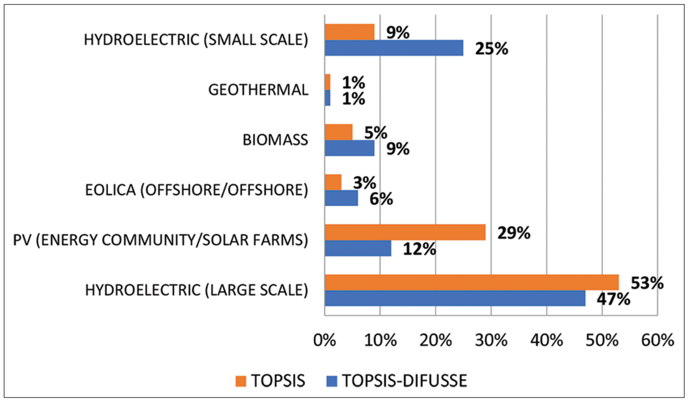


Figure 4: Consideration of alternatives Pacific region 2

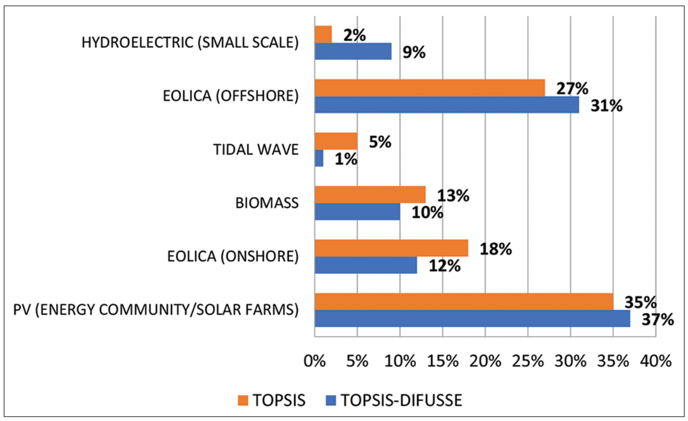
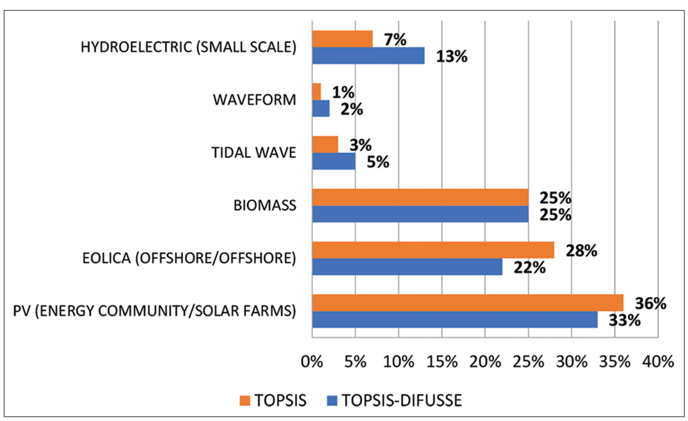


Figure 5: Consideration of alternatives Pacific region 1



As well as the Pacific region, in the Caribbean region two scenarios were evaluated "Caribbean 1" where wind energy technology was not discriminated against, while "Caribbean 2" discriminated between Offshore Wind and Onshore Wind, see Figure 7. The Caribbean region, characterized by its coastal location and its warm climate, is a key area for the implementation of renewable energies in Colombia. Geographically, the region is predominantly flat, with extensive coastal areas and some low mountain ranges. Economically, it stands out for tourism, agriculture (mainly banana and oil palm) and mining. Climatically, the region has a dry tropical climate, with high temperatures and high solar radiation throughout the year. However, in Figure 6 the alternatives that stand out as

Figure 6: Weighting of alternatives Caribbean region 2

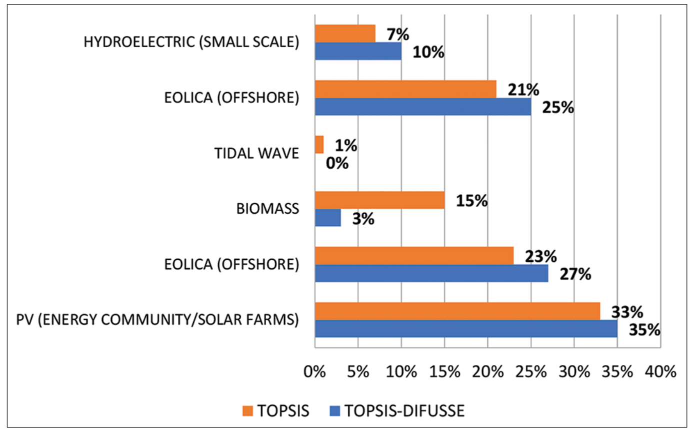
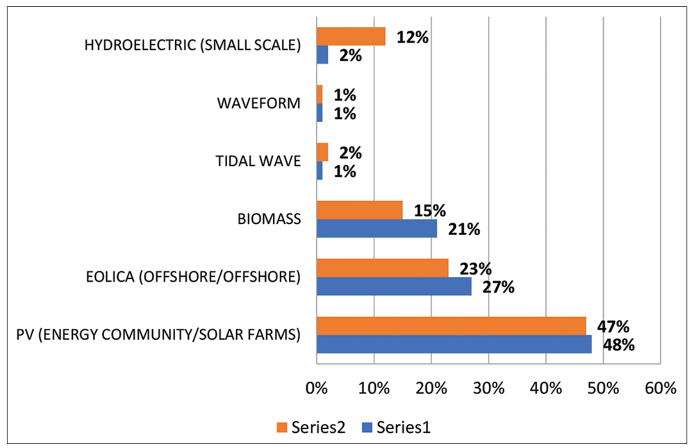


Figure 7: Weighting of alternatives Caribbean region 1



the most relevant for this area of Colombia are solar photovoltaic, Offshore wind and Onshore Wind, with values of 35%, 27% and 25% respectively for the TOPSIS-DIFUSSE methodology. The hierarchy by the TOPSIS method yields the same hierarchy as the previous methodology, varying only the weighting of these, in such a way that it serves to strengthen the decision-making on the best source of energy for this area of the country.

4. CONCLUSIONS AND RECOMMENDATIONS

As a conclusion of the implemented methodologies, the results of this investigation are striking, in most of the regions the hierarchizations did not change, only the percentage weighting of the results for each alternative varied, however the values of the results of TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and Fuzzy TOPSIS may have equal or different percentage weighting due to the differences in how each method handles uncertainty and subjectivity in the data and decision preferences. For example, in the TOPSIS methodology, Deterministic data, it is assumed that the data and the preferences of the criteria are deterministic and accurate. Each criterion is evaluated with exact values and fixed weights, while for the direct calculation, the distances between each alternative and the ideal (best) and anti-ideal (worst) solutions are calculated directly and the ranking is determined based on these distances. While in TOPSIS-DIFFUSE the treatment of uncertainty and subjectivity, it incorporates fuzzy set theory to handle the uncertainty and subjectivity inherent in data and preferences. It uses fuzzy numbers to represent the values and the weights, which allows greater flexibility and realism when modeling real-world problems, likewise the weights and the evaluations of the criteria can vary within a fuzzy range, which better reflects the uncertainty and variability in the opinions of experts. The equality in some of the weights may be due to the fact that in some cases, the percentage weights may be equal if the preferences and the relative importance of the criteria are clear and do not vary significantly between the methods. This can happen when there is consensus among experts or when the data are quite accurate, if the decision environment is relatively stable and well understood, the weights in TOPSIS and fuzzy TOPSIS may coincide, on the other hand the difference between some alternative weights may occur due to arise when there is greater uncertainty and ambiguity in the data. Fuzzy TOPSIS allows to model these uncertainties, resulting in weightings that reflect ranges of possible values instead of single values, finally the subjective preferences of decision makers can be more complex and nuanced in practice. Fuzzy TOPSIS captures these subjective variations better than conventional TOPSIS, resulting in different weights.

As a conclusion of the hierarchization and weighting of energies in the Colombian territory, this research highlights that three were the most preferred alternatives as sources of energization, which were solar photovoltaic, Wind and Biomass, these alternatives were present in each of the regions and also counted on always being among some of the 3 most important in the study region, is that Colombia has a high potential for solar photovoltaic energy, especially in the Caribbean and Orinoquia regions. These areas are characterized by high levels of solar radiation throughout the year, which allows a constant and efficient generation of electricity. In the Caribbean, for example, the abundance of sunshine makes the installation of solar panels highly effective, reducing dependence on fossil fuels and promoting sustainability. The implementation of solar photovoltaic energy in these regions not only provides a clean and renewable energy source, but also creates employment opportunities and local economic development, promoting a just energy transition by improving the quality of life of communities and reducing economic inequalities. Wind energy is particularly suitable for the Caribbean and Pacific regions due to the strong and constant winds that are recorded in these areas. In the Caribbean Region, wind currents are ideal for the installation of wind farms, which can generate large amounts of electricity in a sustainable way. In the Pacific Region, the topography and the influence of ocean currents also favor the generation of wind energy. The implementation of wind projects in these areas helps to diversify the country's energy matrix, reduce greenhouse gas emissions and take advantage of natural resources that would otherwise be underutilized. In addition, the development of wind energy can attract investments and foster technical training in local communities, promoting an inclusive and equitable energy transition. Biomass is a particularly viable renewable energy source in the Amazon and Andean regions, despite the hierarchy occupied in this research, where the abundance of organic resources and agricultural waste can be used for energy generation. In the Amazon, biomass can take advantage of waste from agriculture and forestry, providing an energy solution that is both ecologically sustainable and economical. In the Andean Region, agricultural and livestock waste can be converted into biogas or electricity, promoting the efficient use of local resources and reducing dependence on non-renewable energy sources. The use of biomass also contributes to waste management and climate change mitigation, while providing a source of additional income for rural communities, fostering a just and sustainable energy transition.

Finally, the implementation of these renewable energy sources in Colombia not only addresses the need to reduce carbon emissions and combat climate change, but also facilitates a just energy transition by promoting social and economic inclusion. Solar photovoltaics, wind and biomass have the potential to generate employment, improve local infrastructure and provide access to clean energy to communities that have historically been marginalized or dependent on polluting and expensive energy sources. The diversification of the energy matrix through these technologies also reduces the country's vulnerability to fluctuations in the fossil fuel market and strengthens energy security. At the same time, the development of renewable projects promotes the decentralization of energy generation, empowering local communities and encouraging participation in the management of their energy resources.

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