

A Grey Fuzzy Comprehensive Evaluation and Analysis Method for Clean Energy Capability: A Case Study of African Clean Energy

Weiming Yang

Department of Management, Party School of the Guangdong Provincial Committee of CPC, Guangzhou, China
Email: yangweiming626@163.com

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Abstract

An evaluation index system for clean energy potential based on the PSR (Pressure-State-Response) model is established in this paper. The index system includes wind energy, hydropower, and solar energy reserves, technical and economic feasibility of development, policy environment, and other relevant indicators. Subsequently, a multi-level ordinal relationship analysis method is used to determine the weights of each hierarchical index. Finally, a new fuzzy evaluation method is developed to assess Africa's clean energy potential. This research can enhance the understanding of Africa's clean energy potential, promote the development and investment in clean energy bases, accelerate clean development, and foster a new interconnected energy landscape in Africa centered around clean energy.

Keywords

Grey Fuzzy Comprehensive Evaluation, Africa's Clean Energy Potential, Pressure-State-Response Model

1. Introduction

According to statistics from the International Renewable Energy Agency (IRENA), Africa possesses 60% of the world's solar resources, 30% of hydropower resources, as well as rich geothermal, wind, and biomass reserves. However, current installed capacity of clean energy only accounts for 2% of the global total, with approximately 600 million people lacking access to reliable electricity. This significant disparity between resource potential and actual development levels underscores the strategic value of systematically evaluating Africa's clean energy potential. Nevertheless, existing research predominantly focuses on techno-economic anal-

ysis of single types of energy, neglecting multidimensional considerations such as regional heterogeneity, policy uncertainty, and social acceptance. In particular, there are problems such as data deficiency, ambiguous assessment criteria, and incomplete decision-making information in energy data. This paper innovatively constructs a grey fuzzy comprehensive evaluation model, integrating grey system theory with fuzzy mathematics methods, aiming to overcome the dual constraints of data paucity and decision-making ambiguity in Africa's clean energy development. This study not only aids in revealing spatial distribution characteristics and development priorities of Africa's clean energy resources but also holds significant practical implications for promoting the implementation of the "Africa Renewable Energy Initiative" and contributing to achieving global carbon neutrality goals.

Some scholars have explored the research on clean energy in Africa. Akrofi, M.M. [1] performed a systematic review of 26 studies from 11 countries to identify and describe injustices in renewable energy projects in Africa. Shen, W. [2] explored China's increasing involvement in the development and transfer of renewable energy technologies in Africa, investigating the main drivers and barriers affecting Chinese investments and exports in this sector. Li N. [3] used panel data from selected African countries to examine the concept of clean energy and its impact on food security. AU Mulugetta *et al.* [4] examined the policy impacts of just transitions, ensuring that efforts guiding Africa towards a low-carbon future are supported fairly and equitably. Odarno, L. [5] analyzed the adoption status of clean energy in Sub-Saharan Africa, the role of social inclusion in promoting clean energy adoption, and the challenges of using SSA's social inclusion strategies to promote clean energy adoption. While considerable research has been done on various aspects of Africa's clean energy [6] [7], few studies comprehensively assessed the potential across individual African countries, which is crucial for the exploitation and utilization of energy and environmental protection. In the process of analyzing energy potential, this paper adopts a grey fuzzy comprehensive evaluation approach for assessment and analysis. The primary research structure is shown in **Figure 1**.

2. Indicator Selection

The establishment of a scientifically sound evaluation indicator system directly impacts the accuracy of the evaluation results. A scientific and systematic evaluation indicator system must align with optimization goals in economic, social, environmental, and other aspects, reflecting an overall, comprehensive assessment while considering the objective regional differences. This paper adopts the principles of the PSR model to determine the selection of indicators. Internationally, the setting of energy potential evaluation indicators is typically based on multidimensional considerations, including but not limited to resource availability, technical feasibility, economics, environmental impact, and social acceptance. These evaluation indicators assist decision-makers in understanding the potential value of different forms of energy and their applicability in specific regions or contexts.

issue; it also involves techno-economic factors. For instance, assessing a region's solar energy potential requires considering sunlight hours, land availability, investment costs, grid access, etc. The PSR model might need to be expanded to incorporate economic and technical indicators, rather than focusing solely on environmental pressures. For example, pressure could include growing energy demands, the state might encompass clean energy resources and technology maturity, and responses could involve subsidies, research and development investments, etc.

Traditional resources and energy are relatively finite. With rapid socio-economic development, energy resources are being consumed in large quantities. The development and utilization of renewable energy resources represent a strategic approach to promote the sustainable development of energy resources, contributing to improving energy resource utilization efficiency. Methods for assessing renewable energy resources facilitate the scientific exploitation and utilization of these resources, providing crucial data support for comprehensive planning of renewable energy resources.

2.1. Pressure Indicators

In the field of clean energy, the “pressure indicators” selected in this paper do not directly apply the concept of “pressure” in the PSR model, but rather use its framework to evaluate various factors influencing the development of clean energy. In this context, “pressure indicators” are understood as those challenges or limitations that impact the development and utilization of clean energy, including energy scarcity situations.

Specifically, in the assessment of clean energy potential, pressure indicators mainly include the following categories. Resource availability: This refers to the actual presence and technically exploitable levels of renewable energy sources within a specific region. For example, the feasibility and scale of renewable energy projects can be determined through the evaluation of solar radiation or wind speed data in a given region. Technical and Economic Barriers: These encompass factors such as technological maturity, cost-benefit analysis, and market acceptance. If the cost of a particular clean energy technology is too high or its efficiency is low, it constitutes a “pressure” that hinders its widespread adoption and development. For instance, high initial investment costs for solar panels or wind turbines may deter investors and slow down project implementation. Social Acceptance and Infrastructure: Public attitudes towards new clean energy installations and the capability of existing power grids to effectively integrate and distribute new energy sources are crucial considerations. Environmental Impact: Although clean energy is more environmentally friendly compared to traditional fossil fuels, its production and operation can still cause certain environmental problems, such as noise from wind turbines and pollution during the manufacturing process of photovoltaic panels. These issues also constitute pressures on the development of clean energy.

The energy demand gap and energy security pressures in Africa are two complex and interrelated issues that collectively reflect the challenges faced by the continent in meeting the growing energy needs of its residents and industries. On one hand, with the rapid population growth and urbanization, the demand for electricity is increasing rapidly. However, existing infrastructure cannot keep up with this growth, leading to significant supply-demand imbalances. On the other hand, the acceleration of industrialization has increased the demand for stable and reliable energy, but many African countries still rely on traditional biomass energy (such as firewood), which is inefficient and causes serious indoor air pollution. Especially in rural areas, limited grid coverage results in a large portion of the population lacking access to the power system. According to data, only one-third of households in Sub-Saharan Africa's rural areas have access to electricity. Moreover, despite Africa's abundant renewable resources like solar and wind energy, insufficient funding and technological limitations have hindered their full exploitation.

Regarding energy security pressures, African countries face frequent power outages due to weak infrastructure and outdated technology, affecting daily life and industrial production. Fluctuations in international fossil fuel prices also affect the economic stability of African countries dependent on imported energy. High energy costs constrain corporate competitiveness and development potential. Additionally, frequent extreme weather events, such as droughts and floods, pose threats to critical energy facilities like hydropower stations, increasing the risk of energy supply.

Stress indicators involve numerous influencing factors. In this paper, the fuzzy comprehensive evaluation method is adopted to determine these indicators. This method is particularly suitable for handling complex issues with unclear boundaries and difficult quantification. It leverages concepts from fuzzy mathematics to convert non-quantifiable factors into forms that can be mathematically processed, thereby achieving a comprehensive assessment of multiple influencing factors.

Fuzzy comprehensive analysis is an evaluation method based on fuzzy mathematics theory, especially suitable for dealing with complex issues with unclear boundaries and difficulties in quantification. This method effectively converts qualitative information into quantitative data, thus enabling comprehensive consideration of multiple uncertain factors. Specifically, fuzzy comprehensive analysis first constructs a set of all potential influencing factors and sets corresponding evaluation criteria according to actual conditions. Next, through expert scoring or surveys, membership values of each factor relative to different evaluation grades are obtained, forming a fuzzy judgment matrix. Then, weight coefficients for each factor are calculated. Finally, combining fuzzy operations, the ultimate comprehensive evaluation result is derived. Through this systematic and structured approach, fuzzy comprehensive analysis helps identify solutions to overcome data insufficiencies or partial applicability issues inherent in traditional statistical methods, making the decision-making process more reasonable and

forward-looking.

2.2. State Indicators

The energy state indicators discussed in this paper primarily refer to the basic reserves, development costs, and exploitable duration of wind energy, solar energy, and hydropower. The primary data sources for these indicators come from the Global Internet Development Cooperation Organization.

Hydropower Resources: It is essential first to clarify the river basin conditions within the area and the current stage of river development and utilization. If the rivers in the area are relatively flat and surrounded by many residents and farmland, the conditions for developing hydropower resources are less favorable, making it difficult to implement cascaded hydroelectric power stations. Therefore, hydropower resources in such areas are constrained. Typically, exploitable hydropower resources are concentrated in the upstream sections of rivers where there is a significant drop and canyon-like terrain, which is ideal for constructing dams to maximize hydropower utilization. The evaluation of hydropower resources is the foundation of hydropower resource development and utilization, with a focus on the evaluation of hydrological data such as water flow rate. This assessment mainly involves converting river hydropower into other forms of energy, most commonly electricity, and determining both technically and economically feasible development capacities.

Solar Energy: The state indicators for solar and wind energy focus on aspects such as the basic reserves, development costs, and exploitable duration of these renewable energy sources. **Development Costs:** It involves the technical and economic investments required to capture and convert these energies into usable forms, including equipment manufacturing, installation, and maintenance costs. **Exploitable Duration:** It refers to the length of time these energies can sustainably supply based on current technology levels and consumption rates.

Wind Energy: With the assistance of GIS technology, interpolation mapping of wind energy resources can be performed within the region. Based on the scale and distribution of wind farm construction land, the total exploitable wind energy resources can be calculated. Wind energy resources are generally more abundant during monsoon periods, especially in coastal hilly areas due to favorable terrain conditions suitable for large-scale wind farms. Wind energy assessments require collecting long-term wind data, including representative annual average wind speeds, monthly average wind speeds, hourly average wind speeds, and wind direction data. The evaluation criteria for wind energy resources should be based on wind power density, wind direction frequency, and the distribution of wind energy density directions.

Solar Energy: Assessing solar energy reserves relies on meteorological observation methods and surface radiation data, focusing on both photothermal and photovoltaic applications of solar energy. The amount of solar energy resources does not equate to the exploitable quantity. The obtainable amount depends on the

land construction scale of photovoltaic power plants within the region. The number of photovoltaic power plants in regions rich in climate resources but unsuitable for agricultural or industrial development can be calculated to determine the regional solar energy resource scale and ultimately accurately assess the exploitable solar energy resources in the region by the GIS technology.

2.3. Response Indicators

This paper focuses on the market regulation and fiscal support policies within the power industry. These elements are crucial for promoting the development of clean energy, optimizing energy structures, and achieving peak carbon emissions and carbon neutrality goals.

For clean energy, a reasonable market entry mechanism can ensure fair competition opportunities. Market entry also involves support policies for new entrants, such as priority access rights, which help enhance the investment attractiveness of clean energy projects, encouraging more capital and technology to flow into this sector. Pricing mechanisms are another key factor influencing the development of clean energy. Currently, many countries adopt renewable portfolio standards (RPS) or green certificate trading systems to encourage the use of clean energy. These mechanisms guide resource allocation through market price signals, incentivizing power generation companies to increase their investment in clean energy. Additionally, time-of-use pricing policies adjust electricity prices based on supply and demand at different times, making clean energy more economically valuable during peak hours, thus enhancing its competitiveness.

In terms of fiscal subsidies and support, direct subsidies are a common form of government financial support aimed at promoting clean energy development. They compensate for initial project costs, reduce investor risks, and improve project economic benefits. For instance, during the construction of wind farms, government-provided construction subsidies can cover part of the equipment purchase fees or installation costs.

Tax incentives are also significant fiscal support measures. By reducing or exempting related taxes or providing tax credits, they effectively alleviate the financial burden on clean energy companies. For example, exemptions from import tariffs on clean energy production equipment or reductions in corporate income tax not only lower operational costs but also promote the development of the entire industrial chain, from raw material supply to final product manufacturing and service provision, creating a virtuous cycle.

Furthermore, clean energy projects often require substantial upfront investments. Some governments provide financing facilitation through special loan programs, guarantee mechanisms, and other means. For example, establishing clean energy development funds specifically to offer low-interest or interest-free loans to qualified projects, or raising funds through issuing green bonds, expanding financing channels, and attracting more private capital to participate in the clean energy industry.

In summary, market regulation and fiscal support policies in the power industry play indispensable roles in the development of clean energy. Through market-oriented reforms, grid integration and management, direct subsidies, tax incentives, research and development funding, and financing facilitation, these policies not only create a favorable market environment for clean energy but also provide solid guarantees and support for investors. Therefore, clean energy response indicators, including market regulation in the power industry, fiscal support policies, land and labor support policies, etc., are selected for evaluation in this paper. Specific indicators are shown in **Table 1**.

Table 1. Evaluation index system for clean energy potential in Africa.

| target layer | critierion layer | index level | directivity | |
|--|---|---|--|---|
| Clean energy potential evaluation index system | pressure | Energy demand gap | – | |
| | | Energy security pressure | – | |
| | state | Water energy base | Theoretical implication (PWh/a) | + |
| | | | Theoretical reserves (PWh/a) | + |
| | | Wind energy base | Exploitable hours (h) | + |
| | | | Average development Cost (dollar/kWh) | – |
| | | Solar energy Basis | Theoretical reserve capacity (PWh/a) | + |
| | | | Exploitable hours (h) | + |
| | goal of development | Average development Cost (dollar/kWh) | – | |
| | | Proportion of clean energy generation | + | |
| | Power industry market control | Clean energy project targets | + | |
| | | Market competition level | + | |
| | response | Fiscal support policy | Electricity price regulation | + |
| | | | Power investment | + |
| | | | Preferential loans for clean energy projects | + |
| | | Factors such as land labor support policy | Tax incentives for clean energy power | + |
| Land use preferential policies | | | + | |
| | Labor use policies | + | | |
| | Environmental requirements for resource use | + | | |

2.4. Research Object

The scope of this paper covers 52 major countries and regions in Africa: Algeria, Egypt, Ethiopia, Angola, Benin, Botswana, Burkina Faso, Burundi, Equatorial Guinea, Togo, Eritrea, Cape Verde, The Gambia, Republic of the Congo (Congo-Brazzaville), Democratic Republic of the Congo (Congo-Kinshasa), Djibouti, Guinea, Guinea-Bissau, Ghana, Gabon, Cameroon, Comoros, Côte d'Ivoire, Kenya, Lesotho, Liberia, Libya, Rwanda, Madagascar, Mali, Mauritius, Mauritania, Morocco, Mozambique, Namibia, South Africa, Niger, Nigeria, Sierra Leone, Senegal, Seychelles, São

Tomé and Príncipe, Eswatini (formerly Swaziland), Sudan, Somalia, Tanzania, Tunisia, Uganda, Western Sahara (non-autonomous territory), Zambia, Chad, and the Central African Republic.

This comprehensive coverage allows for an in-depth analysis of the energy landscape across these diverse nations and regions, providing valuable insights into their respective challenges and opportunities in the context of clean energy development and utilization.

3. Research Methodology

3.1. Fuzzy Evaluation Analysis Method

First, the first-level evaluation indicators are established. Based on the evaluation indicator system, set up an evaluation indicator set. The evaluation indicator set includes various indicators that influence the risk of significant misstatement. The evaluation indicator set is represented as $U = \{U_1, U_2, \dots, U_n\}$. Next, the second-level evaluation indicators, denoted as $U = \{u_{i1}, u_{i2}, \dots, u_{im}\}$ ($i = 1, 2, \dots, N$), indicating that U_i contains several factors are established.

In the evaluation indicators, the relative importance of each indicator is its weight. Reasonably determining and appropriately adjusting the weights of the indicators reflects the distinction between primary and secondary aspects in comprehensive evaluations. When analyzing factors, follow the principle of prioritizing more critical elements over less important ones. The optimal factors are selected to analyze their impact and ensure objective and truthful evaluation. The evaluation set consists of all possible overall evaluation results that evaluators might make for the evaluated object. The size of the evaluation set can be determined based on the actual degree of subdivision and computational requirements. For example, it can be divided into five levels: Full, Good, Average, Low, and None.

Fuzzy Comprehensive Evaluation: The first-level fuzzy comprehensive evaluation set is:

$$B_{ij} = A_{ij}R_{ij} = (a_{ij1}, a_{ij2}, \dots, a_{ijm}) \begin{bmatrix} r_{11}^{ij} & \cdots & r_{1k}^{ij} \\ \vdots & \ddots & \vdots \\ r_{m1}^{ij} & \cdots & r_{mk}^{ij} \end{bmatrix} = (b_{ij1}, b_{ij2}, \dots, b_{ijm})$$

The vector $(b_{ij1}, b_{ij2}, \dots, b_{ijm})$ represents the degree of membership of factors u to the evaluation criteria V_1, V_2, \dots, V_n . In the second-level fuzzy comprehensive evaluation, the principle followed is to evaluate based on all factors within the factor subset. Therefore, the single-factor evaluation matrix for U is:

$$R = B_i = \begin{bmatrix} b_{11} & \cdots & b_{1k} \\ \vdots & \ddots & \vdots \\ b_{N1} & \cdots & b_{Nk} \end{bmatrix}$$

For the processing of evaluation indicators, commonly used methods include the Maximum Membership Degree Method, Fuzzy Distribution Method, and

Weighted Average Method. These methods aim to assess the actual situation of the object from a more realistic, reliable, and comparable perspective, ultimately providing an overall evaluation that reasonably integrates these attributes or factors.

When the evaluation object involves qualitative indicators, the evaluation results are typically categorized into five levels: Excellent, Good, Average, Low, and None. The overall situation is then assessed based on the scores obtained.

To objectively determine the evaluation indicators, extensive literature reviews, surveys, and expert interviews are conducted. Ultimately, the evaluation indicators are finalized through these methods. By distributing questionnaires or conducting interviews, each respondent is asked to provide a rating for each second-level indicator. The final step involves statistical analysis to determine the membership degree of each second-level indicator, calculated as: Number of occurrences of this indicator/Total number of trials.

3.2. Determination of Index Weights Based on Order Analysis Method

Determining Indicator Weights Using the Analytic Hierarchy Process

(1) Importance ranking of indicators: Experts rank the relative importance of both first-level and second-level indicators. The ranking is denoted as $U_1 > U_2 > \dots > U_{n-1} > U_n$, where $U_i > U_j$, indicates that within the same level, indicator i is more important than or equally important to indicator j .

(2) Value assignment of indicator importance:

Define the importance ratio between two consecutive indicators at the same level, U_{i-1} and U_i , as r_i .

$$r_i = \frac{W_{i-1}}{W_i}$$

where W_{i-1}, W_i are the weights of the $i-1$ -th, i -th indicators, respectively. The assignment rules for r_i are shown in **Table 2**.

(3) Calculation of Indicator Weights

From the previous equations, we know:

$$\prod_{i=k}^n r_i = \frac{W_{k-1}}{W_k} \frac{W_k}{W_{k+1}} \dots \frac{W_{n-2}}{W_{n-1}} \frac{W_{n-1}}{W_n} = \frac{W_{k-1}}{W_n}$$

Summing from 2 to n , we can get that:

$$\sum_{k=2}^n \left(\prod_{i=k}^n r_i \right) = 1 + \sum_{k=2}^n \frac{W_{k-1}}{W_n} = \frac{W_n}{W_n} + \sum_{k=2}^n \frac{W_{k-1}}{W_n} = \frac{1}{W_n}$$

Therefore, once the relative weight of the last indicator is determined, the relative weights of the other indicators can be calculated. The weight of the last indicator can be calculated by:

$$W_n = \left[1 + \sum_{k=2}^n \frac{W_{k-1}}{W_n} \right]^{-1}$$

The weights of other indicators are: $W_{n-1} = r_n W_n$.

Table 2. r_i assignment rules.

| r_i | Rating description |
|-------|--|
| 1 | U_{i-1} is of Equal Importance to U_i |
| 1.2 | U_{i-1} is Slightly More Important than U_i |
| 1.4 | U_{i-1} is More Important than U_i |
| 1.6 | U_{i-1} Much More Important than U_i |
| 1.8 | U_{i-1} is Extremely More Important than U_i |

Note: The values 1.1, 1.3, 1.5, and 1.7 represent the median values between two adjacent scales.

3.3. Construction of Evaluation Model Based on TOPSIS and Grey Relational Analysis

The study of clean energy in Africa is a multi-layered and complex issue that can be addressed using a combination of the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Grey Relational Analysis (GRA). These methods allow for the integration and concretization of multi-layer indicators. The decision-making principles and bases of these two methods differ, providing good complementarity. This paper combines TOPSIS and GRA to establish an evaluation model for the potential of clean energy in Africa. The decision-making process of the model is as follows:

Step 1: based on the clean energy potential evaluation indicator system, the evaluation objects are determined that raw data are collected, and can be formed the initial decision matrix: $X = (x_{ij})_{m \times n}$.

Where m is the number of evaluation units, n is the number of evaluation indicators, $n = 38$. x_{ij} represents the attribute value of the i -th evaluation unit under the j -th indicator. The first step involves normalizing the indicators to obtain the normalized decision matrix: $V = (v_{ij})_{m \times n}$

$$v_{ij} = \frac{x_{ij} - \min_n \{x_{ij}\}}{\max_n \{x_{ij}\} - \min_n \{x_{ij}\}} \quad (\text{forward pointer})$$

$$v_{ij} = \frac{\max_n \{x_{ij}\} - x_{ij}}{\max_n \{x_{ij}\} - \min_n \{x_{ij}\}} \quad (\text{negative pointer})$$

Step 2: Entropy Weight Method is used to determine the Indicator Weights $w_j = (w_1, w_2, \dots, w_n)$

$$p_{ij} = v_{ij} / \sum_{i=1}^m v_{ij}$$

$$e_i = -1 / \ln(m) \sum_{i=1}^m p_{ij} \cdot \ln p_{ij}$$

$$w_j = 1 - e_j \sum_{j=1}^n (1 - e_j)$$

Step 3: Based on index weights, the weighted normalized decision matrix Y is

obtained:

$$Y = (y_{ij})_{m \times n} = (w_i v_{ij})_{m \times n}$$

Step 4: Determining the Positive Ideal Solution (PIS) $L_j^+ = (f_1^+, f_2^+, \dots, f_n^+)$ and Negative Ideal Solution (NIS) $L_j^- = (f_1^-, f_2^-, \dots, f_n^-)$:

$$f_j^+ = \max_i \{y_{ij}\}, \quad f_j^- = \min_i \{y_{ij}\}$$

Step 5: Grey relational coefficients r_i^+ and r_i^- are calculated based on grey relational analysis,

$$\gamma_{oij}^+ = \frac{\min_i \min_j |f_j^+ - y_{ij}| + \rho \max_i \max_j |f_j^+ - y_{ij}|}{|f_j^+ - y_{ij}| + \rho \max_i \max_j |f_j^+ - y_{ij}|}$$

$$\gamma_{oij}^- = \frac{\min_i \min_j |f_j^- - y_{ij}| + \rho \max_i \max_j |f_j^- - y_{ij}|}{|f_j^- - y_{ij}| + \rho \max_i \max_j |f_j^- - y_{ij}|}$$

$$r_i^+ = \frac{1}{n} \sum_{j=1}^n \gamma_{oij}^+, \quad r_i^- = \frac{1}{n} \sum_{j=1}^n \gamma_{oij}^-$$

Step 6: Euclidean distance d_i^+ and d_i^- are calculated by TOPSIS

$$d_i^+ = \sqrt{\sum_{j=1}^n (f_j^+ - y_{ij})^2}, \quad d_i^- = \sqrt{\sum_{j=1}^n (f_j^- - y_{ij})^2}$$

Step 7: The r_i^+ , r_i^- , d_i^+ , d_i^- are dimensionless-Processed

$$R_i^+ = r_i^+ / \max \{r_i^+\}, \quad R_i^- = r_i^- / \max \{r_i^-\}$$

$$D_i^+ = d_i^+ / \max \{d_i^+\}, \quad D_i^- = d_i^- / \max \{d_i^-\}$$

Step 8: relative proximity between the evaluation unit and the "ideal solution" can be calculated S

$$S_i^+ = \alpha R_i^+ + \beta D_i^-$$

$$S_i^- = \alpha R_i^- + \beta D_i^+$$

$$S_i = S_i^+ / (S_i^+ + S_i^-)$$

where α and β are preference coefficients, $\alpha = \beta = 0.5$ in this paper. The larger the value, the higher the score of the evaluation unit, and the greater the potential.

4. Research on the Evaluation and Analysis of Clean Energy in Africa Based on Grey Fuzzy Comprehensive Evaluation

4.1. Determination of Pressure Indicators and Response Indicators Using Fuzzy Evaluation Analysis Method

Determination of Indicator Data

Based on the fuzzy comprehensive evaluation analysis method, this paper reviewed a large number of literature sources and conducted interviews with 30 ex-

perts and relevant personnel from technology companies. Each interviewee was required to provide an evaluation for each secondary indicator, which was used to calculate the degree of membership for each secondary indicator. The evaluations were categorized into five levels: excellent, good, average, poor, and none. The final statistical results are shown in **Table 3**. Each pair of data in the table represents, on the left, the frequency of responses falling within each evaluation category, and on the right, the calculated final degree of membership for each secondary indicator.

Table 3. Membership degree analysis statistics of energy and environmental pressure indicators.

| Country | Enormous | Membership degree | Relatively large | Membership degree | Average | Membership degree | Low | Membership degree | None | Membership degree |
|---|----------|-------------------|------------------|-------------------|---------|-------------------|-----|-------------------|------|-------------------|
| Algeria | 4 | 0.1333 | 8 | 0.2667 | 10 | 0.3333 | 6 | 0.2000 | 2 | 0.0667 |
| Egypt | 4 | 0.1333 | 8 | 0.2667 | 10 | 0.3333 | 6 | 0.2000 | 2 | 0.0667 |
| Ethiopia | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |
| Angola | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |
| Benin | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Botswana | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Burkina Faso | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Burundi | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Equatorial Guinea | 2 | 0.0667 | 5 | 0.1667 | 12 | 0.4000 | 9 | 0.3000 | 2 | 0.0667 |
| Togo | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Eritrea | 2 | 0.0667 | 5 | 0.1667 | 12 | 0.4000 | 9 | 0.3000 | 2 | 0.0667 |
| Cape Verde | 2 | 0.0667 | 5 | 0.1667 | 12 | 0.4000 | 9 | 0.3000 | 2 | 0.0667 |
| The Gambia | 2 | 0.0667 | 5 | 0.1667 | 12 | 0.4000 | 9 | 0.3000 | 2 | 0.0667 |
| Republic of the Congo (Congo Brazzaville) | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |
| Democratic Republic of the Congo (Congo Kinshasa) | 3 | 0.1000 | 6 | 0.2000 | 11 | 0.3667 | 8 | 0.2667 | 2 | 0.0667 |
| Djibouti | 2 | 0.0667 | 5 | 0.1667 | 12 | 0.4000 | 9 | 0.3000 | 2 | 0.0667 |
| Guinea | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Guinea Bissau | 2 | 0.0667 | 5 | 0.1667 | 12 | 0.4000 | 9 | 0.3000 | 2 | 0.0667 |
| Ghana | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |
| Gabon | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Cameroon | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |
| Comoros | 1 | 0.0333 | 4 | 0.1333 | 13 | 0.4333 | 9 | 0.3000 | 3 | 0.1000 |
| Côte d'Ivoire (Ivory Coast) | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |

Continued

| | | | | | | | | | | |
|------------------------------------|---|--------|---|--------|----|--------|---|--------|---|--------|
| Kenya | 4 | 0.1333 | 8 | 0.2667 | 10 | 0.3333 | 6 | 0.2000 | 2 | 0.0667 |
| Lesotho | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Liberia | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Libya | 4 | 0.1333 | 8 | 0.2667 | 10 | 0.3333 | 6 | 0.2000 | 2 | 0.0667 |
| Rwanda | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Madagascar | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Mali | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Mauritius | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Mauritania | 2 | 0.0667 | 5 | 0.1667 | 12 | 0.4000 | 9 | 0.3000 | 2 | 0.0667 |
| Morocco | 3 | 0.1000 | 7 | 0.2333 | 11 | 0.3667 | 7 | 0.2333 | 2 | 0.0667 |
| Mozambique | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |
| Namibia | 2 | 0.0667 | 5 | 0.1667 | 12 | 0.4000 | 9 | 0.3000 | 2 | 0.0667 |
| South Africa | 5 | 0.1667 | 9 | 0.3000 | 9 | 0.3000 | 6 | 0.2000 | 1 | 0.0333 |
| Niger | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Nigeria | 5 | 0.1667 | 9 | 0.3000 | 9 | 0.3000 | 6 | 0.2000 | 1 | 0.0333 |
| Sierra Leone | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Senegal | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |
| Seychelles | 1 | 0.0333 | 4 | 0.1333 | 13 | 0.4333 | 9 | 0.3000 | 3 | 0.1000 |
| São Tomé and Príncipe | 1 | 0.0333 | 4 | 0.1333 | 13 | 0.4333 | 9 | 0.3000 | 3 | 0.1000 |
| Eswatini (formerly Swaziland) | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Sudan | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |
| Somalia | 2 | 0.0667 | 5 | 0.1667 | 12 | 0.4000 | 9 | 0.3000 | 2 | 0.0667 |
| Tanzania | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |
| Tunisia | 3 | 0.1000 | 7 | 0.2333 | 11 | 0.3667 | 7 | 0.2333 | 2 | 0.0667 |
| Uganda | 3 | 0.1000 | 7 | 0.2333 | 10 | 0.3333 | 8 | 0.2667 | 2 | 0.0667 |
| Western Sahara (NonSelf Governing) | 1 | 0.0333 | 4 | 0.1333 | 13 | 0.4333 | 9 | 0.3000 | 3 | 0.1000 |
| Zambia | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Chad | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |
| Central African Republic | 2 | 0.0667 | 6 | 0.2000 | 12 | 0.4000 | 8 | 0.2667 | 2 | 0.0667 |

The final scores of each region are calculated as shown in **Table 4** by the fuzzy comprehensive evaluation method.

Table 4. Scores of evaluation indicators of energy stress in African countries.

| Country | Score | Country | Score |
|--|---------|--------------------------------------|---------|
| Algeria | 77.0000 | Libya | 77.0000 |
| Egypt | 77.0000 | Rwanda | 74.3333 |
| Ethiopia | 75.3333 | Madagascar | 74.3333 |
| Angola | 75.3333 | Mali | 74.3333 |
| Benin | 74.3333 | Mauritius | 74.3333 |
| Botswana | 74.3333 | Mauritania | 73.6667 |
| Burkina Faso | 74.3333 | Morocco | 75.6667 |
| Burundi | 74.3333 | Mozambique | 75.3333 |
| Equatorial Guinea | 73.6667 | Namibia | 73.6667 |
| Togo | 74.3333 | South Africa | 78.6667 |
| Eritrea | 73.6667 | Niger | 74.3333 |
| Cape Verde | 73.6667 | Nigeria | 78.6667 |
| The Gambia | 73.6667 | Sierra Leone | 74.3333 |
| Republic of the Congo (CongoBrazzaville) | 75.3333 | Senegal | 75.3333 |
| Democratic Republic of the Congo (CongoKinshasa) | 75.0000 | Seychelles | 72.0000 |
| Djibouti | 73.6667 | São Tomé and Príncipe | 72.0000 |
| Guinea | 74.3333 | Eswatini (formerly Swaziland) | 74.3333 |
| GuineaBissau | 73.6667 | Sudan | 75.3333 |
| Ghana | 75.3333 | Somalia | 73.6667 |
| Gabon | 74.3333 | Tanzania | 75.3333 |
| Cameroon | 75.3333 | Tunisia | 75.6667 |
| Comoros | 72.0000 | Uganda | 75.3333 |
| Côte d'Ivoire (Ivory Coast) | 75.3333 | Western Sahara (NonSelfGoverning) | 72.0000 |
| Kenya | 77.0000 | Zambia | 74.3333 |
| Lesotho | 74.3333 | Chad | 74.3333 |
| Liberia | 74.3333 | Central African Republic | 74.3333 |

The membership analysis for labor use policies will not be listed in detail here. The final scores for each indicator in each region are calculated as shown in **Table 5** by the fuzzy comprehensive evaluation method.

Resource and environmental data were obtained from statistics compiled by the Global Energy Interconnection Development Cooperation Organization, as shown in **Table 6**.

Table 5. Scores of African countries by indicator.

| Country | Energy demand pressure | Proportion of clean energy power generation | Clean energy project targets | Market competition level | Electricity price control | Electricity investment | Preferential loans for clean energy projects | Tax incentives for clean energy electricity | Land use preferential policies | Labor force use policies | Environmental requirements for projects |
|---|------------------------|---|------------------------------|--------------------------|---------------------------|------------------------|--|---|--------------------------------|--------------------------|---|
| Algeria | 78.67 | 71.33 | 70.00 | 86.00 | 82.33 | 86.00 | 80.67 | 83.33 | 81.67 | 82.67 | 83.33 |
| Egypt | 78.67 | 76.00 | 76.67 | 76.33 | 79.67 | 81.33 | 80.00 | 83.00 | 83.67 | 82.00 | 82.67 |
| Ethiopia | 77.33 | 75.67 | 76.67 | 70.67 | 69.33 | 81.67 | 75.67 | 76.00 | 74.00 | 75.67 | 74.67 |
| Angola | 77.33 | 80.67 | 82.00 | 80.00 | 79.67 | 83.83 | 80.67 | 80.33 | 80.67 | 81.33 | 82.67 |
| Benin | 75.67 | 73.33 | 73.00 | 72.00 | 73.67 | 71.67 | 73.67 | 74.00 | 74.33 | 72.00 | 75.00 |
| Botswana | 75.67 | 79.67 | 81.67 | 80.67 | 80.33 | 78.67 | 80.00 | 78.00 | 78.67 | 81.00 | 83.00 |
| Burkina Faso | 75.67 | 79.00 | 80.33 | 81.33 | 73.67 | 80.00 | 78.67 | 80.67 | 78.67 | 80.67 | 79.00 |
| Burundi | 75.67 | 78.67 | 77.67 | 78.33 | 78.67 | 77.33 | 79.67 | 80.00 | 80.00 | 80.33 | 81.33 |
| Equatorial Guinea | 75.67 | 73.67 | 74.00 | 69.67 | 72.00 | 72.67 | 75.33 | 74.00 | 74.00 | 75.33 | 74.67 |
| Togo | 75.67 | 79.67 | 79.00 | 71.00 | 71.00 | 68.00 | 70.00 | 70.67 | 67.67 | 69.00 | 67.00 |
| Eritrea | 75.67 | 77.67 | 77.00 | 78.33 | 76.33 | 76.00 | 77.67 | 78.33 | 78.67 | 78.33 | 78.33 |
| Cape Verde | 75.67 | 79.67 | 83.00 | 83.00 | 77.00 | 81.33 | 75.33 | 74.33 | 73.33 | 73.33 | 76.00 |
| The Gambia | 75.67 | 77.33 | 80.00 | 74.00 | 75.67 | 73.33 | 76.33 | 75.33 | 73.33 | 74.67 | 73.00 |
| Republic of the Congo (CongoBrazzaville) | 77.33 | 80.33 | 81.00 | 79.67 | 82.33 | 83.33 | 77.33 | 79.33 | 79.67 | 79.67 | 79.67 |
| Democratic Republic of the Congo (CongoKinshasa) | 77.00 | 64.00 | 65.67 | 69.00 | 67.33 | 84.67 | 76.00 | 74.67 | 76.00 | 75.67 | 75.00 |
| Djibouti | 75.67 | 79.33 | 80.00 | 77.67 | 78.33 | 80.00 | 79.00 | 78.33 | 76.00 | 77.33 | 79.33 |
| Guinea | 75.67 | 77.00 | 74.67 | 83.00 | 82.67 | 82.00 | 75.67 | 75.33 | 84.67 | 82.33 | 82.67 |
| GuineaBissau | 75.67 | 74.67 | 76.00 | 74.33 | 76.00 | 74.67 | 74.33 | 75.33 | 74.67 | 75.33 | 75.00 |
| Ghana | 77.33 | 82.33 | 84.33 | 82.67 | 82.67 | 84.00 | 80.33 | 80.00 | 79.67 | 80.67 | 81.33 |
| Gabon | 75.67 | 80.33 | 80.33 | 80.67 | 82.67 | 81.00 | 81.33 | 80.67 | 80.33 | 82.00 | 82.00 |
| Cameroon | 77.33 | 82.00 | 82.00 | 75.33 | 74.00 | 79.67 | 74.00 | 75.67 | 75.67 | 74.67 | 76.50 |
| Comoros | 74.00 | 72.33 | 72.67 | 77.00 | 74.33 | 73.33 | 75.67 | 71.17 | 71.67 | 74.00 | 74.00 |
| Côte d'Ivoire (Ivory Coast) | 77.33 | 82.00 | 80.33 | 80.33 | 80.67 | 80.00 | 81.67 | 79.67 | 79.33 | 79.67 | 78.67 |
| Kenya | 78.67 | 68.67 | 70.33 | 76.67 | 72.33 | 76.67 | 82.33 | 86.33 | 66.33 | 67.67 | 66.67 |
| Lesotho | 75.67 | 74.33 | 75.67 | 73.33 | 73.67 | 75.33 | 75.33 | 75.33 | 75.33 | 73.00 | 75.67 |
| Liberia | 75.67 | 75.00 | 76.33 | 74.67 | 77.00 | 79.67 | 80.00 | 78.00 | 79.00 | 79.33 | 79.67 |
| Libya | 78.67 | 85.67 | 80.67 | 69.00 | 67.33 | 68.67 | 79.00 | 77.67 | 78.00 | 77.00 | 78.00 |
| Rwanda | 75.67 | 80.67 | 82.00 | 79.67 | 80.33 | 79.33 | 81.00 | 78.67 | 80.67 | 79.00 | 77.67 |
| Madagascar | 75.67 | 77.67 | 75.67 | 71.67 | 75.33 | 75.33 | 78.00 | 72.67 | 78.00 | 75.00 | 76.00 |
| Mali | 75.67 | 81.00 | 79.67 | 101.33 | 77.67 | 80.00 | 79.67 | 80.67 | 80.67 | 80.33 | 80.00 |

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|------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Mauritius | 75.67 | 80.00 | 80.00 | 69.00 | 70.67 | 82.67 | 76.33 | 78.67 | 78.00 | 78.00 | 76.33 |
| Mauritania | 75.67 | 86.33 | 84.00 | 83.00 | 83.33 | 84.67 | 75.00 | 78.67 | 79.67 | 79.00 | 79.00 |
| Morocco | 77.33 | 81.33 | 82.33 | 78.00 | 74.33 | 77.33 | 78.67 | 80.67 | 74.67 | 77.00 | 78.00 |
| Mozambique | 77.33 | 85.67 | 85.00 | 84.33 | 86.33 | 74.67 | 69.00 | 66.67 | 73.67 | 74.67 | 75.67 |
| Namibia | 75.67 | 81.33 | 80.67 | 70.00 | 71.67 | 82.33 | 75.33 | 80.33 | 71.00 | 68.67 | 68.33 |
| South Africa | 80.00 | 73.67 | 74.67 | 74.33 | 75.33 | 74.33 | 73.67 | 74.67 | 74.33 | 75.33 | 73.00 |
| Niger | 75.67 | 82.33 | 80.67 | 86.33 | 84.33 | 82.00 | 84.33 | 84.33 | 77.33 | 79.00 | 81.00 |
| Nigeria | 80.00 | 81.33 | 80.00 | 69.67 | 70.00 | 76.00 | 70.00 | 70.00 | 74.67 | 74.33 | 74.67 |
| Sierra Leone | 75.67 | 78.00 | 71.00 | 76.33 | 73.33 | 75.67 | 72.33 | 76.67 | 75.33 | 70.67 | 78.00 |
| Senegal | 77.33 | 74.33 | 75.67 | 74.00 | 74.67 | 73.00 | 74.67 | 74.00 | 75.67 | 75.33 | 74.67 |
| Seychelles | 74.00 | 74.67 | 75.67 | 74.33 | 74.00 | 76.33 | 74.33 | 75.33 | 74.33 | 72.83 | 74.67 |
| São Tomé and Príncipe | 74.00 | 74.67 | 75.00 | 74.33 | 74.33 | 75.00 | 75.00 | 74.00 | 75.33 | 75.33 | 75.67 |
| Eswatini (formerly Swaziland) | 75.67 | 75.67 | 72.33 | 73.67 | 74.67 | 74.67 | 74.33 | 76.00 | 73.67 | 74.67 | 73.33 |
| Sudan | 77.33 | 76.67 | 78.33 | 80.00 | 80.33 | 78.00 | 79.00 | 79.67 | 79.33 | 80.00 | 80.33 |
| Somalia | 75.67 | 86.00 | 85.67 | 73.33 | 75.33 | 67.33 | 83.33 | 84.00 | 73.33 | 76.00 | 75.67 |
| Tanzania | 77.33 | 77.33 | 79.67 | 82.67 | 80.67 | 83.00 | 83.33 | 85.00 | 79.67 | 81.00 | 83.00 |
| Tunisia | 77.33 | 82.00 | 80.00 | 78.67 | 75.67 | 77.33 | 74.67 | 74.67 | 76.67 | 77.33 | 75.00 |
| Uganda | 77.33 | 81.00 | 80.33 | 78.00 | 82.00 | 81.67 | 81.33 | 81.00 | 84.00 | 80.67 | 79.67 |
| Western Sahara (NonSelf Governing) | 74.00 | 80.00 | 76.67 | 81.67 | 80.00 | 82.67 | 80.00 | 81.33 | 81.00 | 77.33 | 78.00 |
| Zambia | 75.67 | 70.33 | 71.33 | 77.33 | 71.33 | 81.67 | 71.00 | 71.67 | 67.33 | 69.00 | 70.33 |
| Chad | 75.67 | 74.33 | 78.67 | 80.00 | 74.67 | 74.00 | 74.67 | 73.33 | 74.67 | 75.33 | 75.00 |
| Central African Republic | 75.67 | 77.00 | 78.00 | 78.67 | 74.33 | 76.00 | 77.00 | 76.00 | 75.33 | 77.67 | 75.33 |

Table 6. Resource base indicators for African countries.

| Country | Average development cost of wind energy (USD /kWh) | Average solar development cost (USD /kWh) | Theoretical implication (PWh/a) | Theoretical reserves (PWh/a) | Exploitable hours (h) | Average development Cost (dollar/kWh) | Theoretical reserve capacity (PWh/a) |
|--------------|--|---|---------------------------------|------------------------------|-----------------------|---------------------------------------|--------------------------------------|
| Algeria | 4.12 | 3.06 | 0.00 | 47353.70 | 2713.00 | 5015.00 | 2713.00 |
| Egypt | 3.62 | 2.29 | 29.49 | 1726.20 | 2600.00 | 2289.50 | 2600.00 |
| Ethiopia | 4.39 | 2.82 | 68.23 | 9638.70 | 2754.00 | 2414.70 | 2754.00 |
| Angola | 5.57 | 2.74 | 347.55 | 5774.30 | 2240.00 | 2625.20 | 2240.00 |
| Benin | 5 | 2.35 | 2.83 | 679.40 | 1625.00 | 226.80 | 1625.00 |
| Botswana | 4.78 | 2.5 | 0.00 | 6302.30 | 2081.00 | 1283.80 | 2081.00 |
| Burkina Faso | 6.75 | 2.58 | 1.31 | 2233.10 | 1704.00 | 580.30 | 1704.00 |

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|--|------|------|---------|----------|---------|---------|---------|
| Burundi | 0 | 2.24 | 0.97 | 42.30 | 0.00 | 51.60 | 0.00 |
| Equatorial Guinea | 0 | 2.52 | 0.26 | 51.60 | 0.00 | 45.20 | 0.00 |
| Togo | 5.04 | 2.32 | 0.62 | 259.50 | 1609.00 | 108.70 | 1609.00 |
| Eritrea | 4.02 | 2.51 | 0.00 | 1469.60 | 2523.00 | 269.00 | 2523.00 |
| Cape Verde | 5.67 | 5.45 | 0.00 | 93.50 | 3093.00 | 6.20 | 3093.00 |
| The Gambia | 5.09 | 3.08 | 0.00 | 96.60 | 1835.00 | 22.60 | 1835.00 |
| Republic of the Congo (Congo Brazzaville) | 0 | 2.68 | 241.31 | 697.10 | 0.00 | 611.70 | 0.00 |
| Democratic Republic of the Congo (Congo Kinshasa) | 4.46 | 3.19 | 1795.01 | 5007.40 | 2028.00 | 4416.70 | 2028.00 |
| Djibouti | 3.24 | 2.19 | 0.00 | 381.10 | 2703.00 | 47.60 | 2703.00 |
| Guinea | 0 | 3.05 | 10.60 | 1042.20 | 0.00 | 500.70 | 0.00 |
| GuineaBissau | 5.15 | 2.2 | 0.00 | 239.10 | 1718.00 | 68.30 | 1718.00 |
| Ghana | 4.68 | 2.36 | 18.95 | 1169.30 | 1740.00 | 446.80 | 1740.00 |
| Gabon | 0 | 2.93 | 154.63 | 518.00 | 0.00 | 432.80 | 0.00 |
| Cameroon | 4.51 | 2.88 | 224.89 | 1395.40 | 1958.00 | 901.10 | 1958.00 |
| Comoros | 0 | 3.98 | 0.00 | 12.40 | 0.00 | 3.20 | 0.00 |
| Côte d'Ivoire (Ivory Coast) | 0 | 2.36 | 0.73 | 1423.30 | 0.00 | 594.20 | 0.00 |
| Kenya | 4.31 | 3.16 | 0.00 | 7662.30 | 2681.00 | 1230.70 | 2681.00 |
| Lesotho | 4.85 | 2.15 | 0.00 | 279.10 | 1944.00 | 61.70 | 1944.00 |
| Liberia | 0 | 3.37 | 0.00 | 271.20 | 0.00 | 171.40 | 0.00 |
| Libya | 4.14 | 2.91 | 0.00 | 31143.50 | 2658.00 | 3635.40 | 2658.00 |
| Rwanda | 0 | 2.32 | 1.70 | 38.90 | 0.00 | 46.60 | 0.00 |
| Madagascar | 4.74 | 3.33 | 0.00 | 19224.60 | 2661.00 | 2766.20 | 2661.00 |
| Mali | 6.67 | 7.02 | 15.56 | 56.10 | 2804.00 | 3.90 | 2804.00 |
| Mauritius | 4.22 | 3.46 | 0.00 | 24268.10 | 2944.00 | 2303.40 | 2944.00 |
| Mauritania | 3.02 | 2.11 | 0.00 | 6297.50 | 2828.00 | 824.10 | 2828.00 |
| Morocco | 4.79 | 2.64 | 0.00 | 6679.40 | 1986.00 | 1549.00 | 1986.00 |
| Mozambique | 4.48 | 2.15 | 44.70 | 9453.80 | 2031.00 | 1932.00 | 2031.00 |
| Namibia | 3.75 | 2.16 | 0.01 | 16870.10 | 2348.00 | 2566.50 | 2348.00 |
| South Africa | 4.66 | 3.14 | 0.00 | 3750.10 | 2002.00 | 1314.60 | 2002.00 |
| Niger | 4.67 | 2.22 | 14.79 | 6076.70 | 1907.00 | 1810.20 | 1907.00 |
| Nigeria | 0 | 2.65 | 213.65 | 235.10 | 0.00 | 136.00 | 0.00 |
| Sierra Leone | 4.05 | 2.5 | 0.00 | 2253.60 | 2187.00 | 416.60 | 2187.00 |
| Senegal | 0 | 0 | 0.00 | 7.60 | 0.00 | 0.80 | 0.00 |

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| | | | | | | | |
|------------------------------------|------|------|--------|----------|---------|---------|---------|
| Seychelles | 0 | 0 | 0.00 | 5.60 | 0.00 | 1.80 | 0.00 |
| São Tomé and Príncipe | 6.88 | 6.26 | 0.00 | 4.70 | 3753.00 | 0.20 | 3753.00 |
| Eswatini (formerly Swaziland) | 3.55 | 2.35 | 0.00 | 32760.40 | 2747.00 | 4299.30 | 2747.00 |
| Sudan | 4.12 | 3.54 | 50.97 | 18234.20 | 3040.00 | 1405.20 | 3040.00 |
| Somalia | 3.9 | 2.55 | 0.00 | 5519.50 | 2258.00 | 1949.00 | 2258.00 |
| Tanzania | 3.17 | 2.3 | 127.34 | 3619.20 | 2757.00 | 300.70 | 2757.00 |
| Tunisia | 5.36 | 3.6 | | 5714.30 | 2353.00 | 1220.00 | 2353.00 |
| Uganda | 0 | 2.22 | 58.45 | 756.80 | 0.00 | 499.60 | 0.00 |
| Western Sahara (NonSelf Governing) | 2.88 | 2.56 | 0.00 | 8495.80 | 3468.00 | 596.50 | 3468.00 |
| Zambia | 4.59 | 2.34 | 204.34 | 5468.00 | 1963.00 | 1621.80 | 1963.00 |
| Chad | 4.23 | 3.37 | 0.00 | 23145.60 | 2987.00 | 2918.10 | 2987.00 |
| Central African Republic | 0 | 3.38 | 77.00 | 2573.40 | 0.00 | 1292.40 | 0.00 |

4.2. Calculation of Weights

This translation accurately captures the methodology used to calculate the weights of the primary indicators by involving expert rankings and applying the r_i value assignment rules, with the final results presented in **Table 7**.

Table 7. Order relationship and importance ratio of first-level indicators.

| expert | Index order relation | r_2 | r_3 | r_4 | r_5 | r_6 | r_7 | r_8 |
|--------|---|-------|-------|-------|-------|-------|-------|-------|
| 1 | $U_7 > U_8 > U_4 > U_3 > U_2 > U_1 > U_5 > U_6$ | 1.2 | 1.4 | 1 | 1 | 1.1 | 1.4 | 1.1 |
| 2 | $U_7 > U_8 > U_3 > U_4 > U_2 > U_1 > U_6 > U_5$ | 1.2 | 1.3 | 1.1 | 1 | 1.1 | 1.3 | 1.2 |
| 3 | $U_8 > U_7 > U_1 > U_2 > U_3 > U_4 > U_5 > U_6$ | 1.1 | 1.6 | 1.4 | 1 | 1 | 1.1 | 1.3 |
| 4 | $U_7 > U_8 > U_4 > U_3 > U_2 > U_1 > U_5 > U_6$ | 1.2 | 1.6 | 1.1 | 1 | 1.2 | 1.3 | 1.2 |

Based on the importance ranking of the primary indicators, the weights are calculated using equations. The resulting weight values for the primary indicators are shown in **Table 8**.

Table 8. Weights of first-level indicators.

| expert | W_1 | W_2 | W_3 | W_4 | W_5 | W_6 | W_7 | W_8 |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1 | 0.110 | 0.122 | 0.122 | 0.122 | 0.079 | 0.072 | 0.204 | 0.170 |
| 2 | 0.108 | 0.119 | 0.130 | 0.119 | 0.069 | 0.083 | 0.203 | 0.169 |
| 3 | 0.131 | 0.093 | 0.093 | 0.093 | 0.085 | 0.065 | 0.209 | 0.230 |
| 4 | 0.093 | 0.111 | 0.111 | 0.122 | 0.071 | 0.059 | 0.235 | 0.196 |

By calculating the average of these 4 sets of data, we can obtain the weight vector for the primary indicators:

For these 3 sets of data, by calculating their average, we can obtain the weight vector for the primary indicators: $W = (0.110, 0.111, 0.114, 0.114, 0.076, 0.070, 0.213, 0.191)$.

Similarly, another 4 experts from related fields were invited to rank the importance of the 8 secondary indicators and assign values to them. This resulted in the importance rankings and corresponding r_i values for each of the 8 secondary indicators, as shown in **Tables 9-22**.

Table 9. The order relationship and importance ratio of U_1 indicators.

| expert | Index order relation | r_2 |
|--------|----------------------|-------|
| 1 | $U_2 > U_1$ | 1.2 |
| 2 | $U_1 > U_2$ | 1.1 |
| 3 | $U_1 > U_2$ | 1.2 |
| 4 | $U_2 > U_1$ | 1.2 |

Table 10. Weights of U_1 indicators.

| expert | W_1 | W_2 |
|--------|-------|-------|
| 1 | 0.455 | 0.545 |
| 2 | 0.524 | 0.476 |
| 3 | 0.545 | 0.455 |
| 4 | 0.455 | 0.545 |

The weight vector of the secondary index of U_1 is obtained by averaging, $W_1 = (0.495, 0.505)$.

Table 11. Sequence relationship and importance ratio of U_3 indicators.

| expert | Index order relation | r_1 | r_2 |
|--------|----------------------|-------|-------|
| 1 | $U_3 > U_1 > U_2$ | 1.4 | 1 |
| 2 | $U_3 > U_2 > U_1$ | 1.3 | 1 |
| 3 | $U_2 > U_3 > U_1$ | 1.1 | 1.4 |
| 4 | $U_3 > U_2 > U_1$ | 1.3 | 1.1 |

Table 12. Weights of U_3 indicators

| expert | W_1 | W_2 | W_3 |
|--------|-------|-------|-------|
| 1 | 0.294 | 0.294 | 0.412 |
| 2 | 0.303 | 0.303 | 0.394 |
| 3 | 0.254 | 0.391 | 0.355 |
| 4 | 0.283 | 0.312 | 0.405 |

The weight vector of the secondary index of U_3 is obtained: $W_3 = (0.284, 0.325, 0.392)$.

Table 13. Sequence relationship and importance ratio of U_4 indicators.

| expert | Index order relation | r_1 | r_2 |
|--------|----------------------|-------|-------|
| 1 | $U_2 > U_3 > U_1$ | 1.1 | 1 |
| 2 | $U_3 > U_1 > U_2$ | 1.4 | 1 |
| 3 | $U_3 > U_2 > U_1$ | 1.3 | 1.1 |
| 4 | $U_3 > U_2 > U_1$ | 1.4 | 1.1 |

Table 14. Weights of U_4 indicators.

| expert | W_1 | W_2 | W_3 |
|--------|-------|-------|-------|
| 1 | 0.323 | 0.355 | 0.323 |
| 2 | 0.294 | 0.294 | 0.412 |
| 3 | 0.283 | 0.312 | 0.405 |
| 4 | 0.275 | 0.302 | 0.423 |

The weight vector of the secondary index of U_4 is obtained: $W_4 = (0.294, 0.316, 0.391)$.

Table 15. Sequence relationship and importance ratio of U_5 indicators.

| expert | Index order relation | r_2 |
|--------|----------------------|-------|
| 1 | $U_1 > U_2$ | 1.2 |
| 2 | $U_1 > U_2$ | 1.3 |
| 3 | $U_1 > U_2$ | 1.2 |
| 4 | $U_2 > U_1$ | 1.1 |

Table 16. Weights of U_5 indicators.

| expert | W_1 | W_2 |
|--------|-------|-------|
| 1 | 0.545 | 0.455 |
| 2 | 0.565 | 0.435 |
| 3 | 0.545 | 0.455 |
| 4 | 0.524 | 0.476 |

The weight vector of the secondary index of U_5 is obtained: $W_5 = (0.545, 0.455)$.

Table 17. Sequence relationship and importance ratio of U_6 indicators.

| expert | Index order relation | r_2 |
|--------|----------------------|-------|
| 1 | $U_2 > U_1$ | 1.4 |
| 2 | $U_1 > U_2$ | 1.2 |
| 3 | $U_1 > U_2$ | 1.1 |
| 4 | $U_1 > U_2$ | 1.2 |

Table 18. Weights of U_6 indicators.

| expert | W_1 | W_2 |
|--------|-------|-------|
| 1 | 0.583 | 0.417 |
| 2 | 0.545 | 0.455 |
| 3 | 0.524 | 0.476 |
| 4 | 0.545 | 0.455 |

The weight vector of the secondary index of U_6 is obtained: $W_6 = (0.550, 0.450)$.

Table 19. Sequence relationship and importance ratio of U_7 indicators.

| expert | Index order relation | r_2 | r_2 |
|--------|----------------------|-------|-------|
| 1 | $U_3 > U_2 > U_1$ | 1.1 | 1.1 |
| 2 | $U_3 > U_1 > U_2$ | 1.2 | 1.2 |
| 3 | $U_2 > U_3 > U_1$ | 1.4 | 1.1 |
| 4 | $U_3 > U_2 > U_1$ | 1.1 | 1.1 |

Table 20. Weights of U_7 indicators.

| expert | W_1 | W_2 | W_3 |
|--------|-------|-------|-------|
| 1 | 0.302 | 0.332 | 0.366 |
| 2 | 0.330 | 0.275 | 0.396 |
| 3 | 0.275 | 0.423 | 0.302 |
| 4 | 0.302 | 0.332 | 0.366 |

The weight vector of the secondary index of U_7 is obtained: $W_7 = (0.302, 0.341, 0.357)$.

Table 21. Sequence relationship and importance ratio of U_7 indicators.

| expert | Index order relation | r_2 | r_2 |
|--------|----------------------|-------|-------|
| 1 | $U_2 > U_1 > U_3$ | 1.1 | 1.1 |
| 2 | $U_1 > U_2 > U_3$ | 1 | 1.2 |
| 3 | $U_2 > U_1 > U_3$ | 1.4 | 1.1 |
| 4 | $U_1 > U_2 > U_3$ | 1.1 | 1.1 |

Table 22. Weights of U_8 indicators.

| expert | W_1 | W_2 | W_3 |
|--------|-------|-------|-------|
| 1 | 0.332 | 0.366 | 0.302 |
| 2 | 0.353 | 0.353 | 0.294 |
| 3 | 0.302 | 0.423 | 0.275 |
| 4 | 0.366 | 0.332 | 0.302 |

The weight vector of the secondary index of U_8 is obtained: $W_8 = (0.302, 0.341,$

0.357).

4.3. Analysis of Africa's Clean Energy Potential Based on Grey Correlation-TOPSIS

The final comprehensive scores of each region are obtained according to part 2.3 of this paper, as shown in **Table 23**.

Table 23. Aggregate score of clean energy potential of African countries.

| Country | Score | Country | Score |
|--|--------|--------------------------------------|--------|
| Algeria | 0.5918 | Libya | 0.5180 |
| Egypt | 0.5759 | Rwanda | 0.4941 |
| Ethiopia | 0.5029 | Madagascar | 0.5034 |
| Angola | 0.5417 | Mali | 0.5118 |
| Benin | 0.4529 | Mauritius | 0.5437 |
| Botswana | 0.5493 | Mauritania | 0.5807 |
| Burkina Faso | 0.5009 | Morocco | 0.5156 |
| Burundi | 0.4959 | Mozambique | 0.4750 |
| Equatorial Guinea | 0.4292 | Namibia | 0.5129 |
| Togo | 0.4091 | South Africa | 0.4479 |
| Eritrea | 0.5407 | Niger | 0.5675 |
| Cape Verde | 0.4791 | Nigeria | 0.3952 |
| The Gambia | 0.4710 | Sierra Leone | 0.4956 |
| Republic of the Congo (Congo Brazzaville) | 0.4925 | Senegal | 0.4214 |
| Democratic Republic of the Congo (Congo Kinshasa) | 0.5078 | Seychelles | 0.4406 |
| Djibouti | 0.5633 | São Tomé and Príncipe | 0.4549 |
| Guinea | 0.4984 | Eswatini (formerly Swaziland) | 0.5218 |
| Guinea Bissau | 0.4729 | Sudan | 0.5502 |
| Ghana | 0.5494 | Somalia | 0.5427 |
| Gabon | 0.5116 | Tanzania | 0.5954 |
| Cameroon | 0.4966 | Tunisia | 0.4805 |
| Comoros | 0.4298 | Uganda | 0.5055 |
| Côte d'Ivoire (Ivory Coast) | 0.4943 | Western Sahara (NonSelfGoverning) | 0.6028 |
| Kenya | 0.4828 | Zambia | 0.4516 |
| Lesotho | 0.4779 | Chad | 0.5052 |
| Liberia | 0.4860 | Central African Republic | 0.4574 |

Based on the results obtained from the table, the clean energy scores of African countries into three categories can be classified to high scores (≥ 0.55), medium scores (0.5 - 0.55), and medium-low scores (0.45 - 0.5).

Among the high-score potential countries, Western Sahara (non-autonomous territory) leads with a score of 0.6028, followed by Tanzania (0.5954), Algeria (0.5918), Mauritania (0.5807), Egypt (0.5759), Niger (0.5675), and Djibouti (0.5633). These countries possess superior natural resource conditions (such as solar, wind, or geothermal energy) or significant policy support. For instance, there are abundant solar energy resources here in North African countries such as Algeria and Egypt; Western Sahara's geographical location is suitable for both wind and solar energy development. The medium-high potential countries include South Africa (0.4479), Ghana (0.5494), Botswana (0.5493), and Sudan (0.5502). There is a certain foundation in clean energy, but it may be limited by technology, funding, or infrastructure in some countries. For example, there is enormous solar potential here in South Africa, but social and economic balance issues need to be addressed in its energy transition process. The medium-low potential countries include Nigeria (0.3952), Senegal (0.4214), Democratic Republic of the Congo (0.5078), and Kenya (0.4828). Lower scores reflect uneven resource distribution, political instability, or insufficient investment. Eastern African countries such as Tanzania and Rwanda perform well overall, possibly due to the development of geothermal and hydropower resources. Although Western Sahara is not yet independent, its high score highlights its natural resource advantages and suggests it could become a focal point for regional cooperation in the future.

For high-score countries, local governments can prioritize large-scale projects to attract international investment. For medium-low score countries, there is a need to strengthen policy support and promote cross-border grid interconnections to share clean energy technologies. In addition, the clean energy potential in Africa shows significant regional differences here. There are obvious advantages here in North and East African countries, while West and Central African countries need to overcome policy and funding bottlenecks. Through regional cooperation and technology transfer, the overall potential can be maximized, contributing to global energy transition.

5. Conclusions

The evaluation of clean energy potential in Africa not only helps identify the strengths and weaknesses of individual countries but also provides important theoretical foundations and practical guidance for achieving sustainable development goals within the region and globally. This is a strategic initiative that benefits current socio-economic development while focusing on long-term ecological benefits. Therefore, this paper proposes an evaluation and analysis method for African clean energy based on grey relational analysis, TOPSIS, and comprehensive fuzzy numbers.

Firstly, based on the PSR (Pressure-State-Response) model, this paper proposes an evaluation index system for clean energy in Africa, including pressure indicators, status indicators, and response indicators. Then, the values of 12 secondary indicators under pressure and response categories are calculated by the fuzzy comprehensive evaluation analysis method. The state indicators were determined based on foundational resource data provided by the Global Energy Interconnection Development Cooperation Organization. Subsequently, the weights for the 19 secondary indicators are derived by the multi-level ordinal relationship method. Finally, the scores for 52 African countries and regions are obtained by the grey relational-TOPSIS integrated evaluation analysis method.

The advantages of the proposed method are as follows: (1) An evaluation and analysis method for African clean energy based on fuzzy grey relational analysis and TOPSIS is proposed. This method converts uncertain factors into quantitative indicators, thereby enhancing the acceptability of the evaluation results. Fuzzy grey relational analysis can assess the degree of association between different factors even when data is incomplete or information is ambiguous, revealing potential strengths and weaknesses in each country's clean energy development. The TOPSIS method calculates the distance of each country from the ideal solution and the negative ideal solution to determine its comprehensive evaluation score, thus ranking the clean energy potential of various countries. This combined approach not only considers the inherent uncertainty of the data but also leverages multi-criteria decision-making techniques to provide more comprehensive and accurate evaluation results. It serves as a powerful tool for policymakers to guide resource allocation and strategic planning. (2) This method enhances the transparency and objectivity of the evaluation process, making the final results easier for all parties to understand and accept. This promotes more effective international cooperation and investment.

In addition, there are also points worth further extension and research. For instance, further research can increase the promotion and utilization of data diversity.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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