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Evaluating Renewable Energy Technologies for Low-Carbon Transition: A Multi-Criteria Decision Technique

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Abstract: This study utilizes the Analytic Hierarchy Process (AHP) to evaluate and prioritize renewable energy technologies for decarbonization in Nigeria, considering five key criteria: cost, CO_2 emission reduction, availability, maintenance, and social acceptance. Expert judgment was used to construct pairwise comparison matrices for these criteria and five renewable energy alternatives: solar photovoltaic (PV), wind, biomass, hydropower, and geothermal. The results reveal CO_2 emission reduction as the most critical factor, receiving a weight of 0.416, followed by availability (0.262) and cost (0.161). Geothermal energy emerged as the highest-ranked option with a priority score of 0.241, indicating its superior potential for decarbonization. Wind and solar PV ranked second and third, with priority scores of 0.226 and 0.203, respectively. Biomass and hydropower scored lower, with priority values of 0.172 and 0.158, respectively. Sensitivity analysis showed that even with a 10% increase in CO_2 reduction weight, geothermal remained the top choice, with a slight increase in score (0.241 to 0.255). These findings offer evidence-based insights for Nigeria's renewable energy policy, emphasizing the need for targeted investments and further exploration of geothermal resources.

Keywords*—Analytic Hierarchy Process (AHP), Decarbonization, Renewable Energy Technologies*

I. INTRODUCTION

The global urgency to mitigate climate change has intensified efforts toward achieving net-zero carbon emissions, particularly through the transition from fossil fuels to cleaner, renewable energy sources. The energy sector accounts for approximately 73% of global greenhouse gas emissions, making it a critical focus for decarbonization strategies [1]. In alignment with the Paris Agreement, many countries, including Nigeria, have pledged to cut emissions and embrace sustainable energy systems [2]. Nigeria, being Africa's most populous nation and largest economy, faces a dual challenge: addressing widespread energy poverty while reducing its carbon footprint [3]. Currently, the country's energy mix remains heavily dependent on fossil fuels, especially oil and gas which contribute over 80% of total energy consumption [4]. Despite abundant renewable energy potential such as high solar irradiance, significant biomass reserves, and untapped hydropower resources renewables account for less than 20% of the national energy supply [5]. Furthermore, more than 40% of the population lacks access to grid electricity, with rural communities disproportionately affected [6]. The integration of renewable energy into Nigeria's power system is constrained by several barriers, including infrastructural deficits, high upfront capital costs, limited technical capacity, and inconsistent policy frameworks [7,8]. Compounding these issues is the challenge of selecting appropriate renewable energy technologies (RETs), which must consider a range of socio-economic, technical, environmental, and geographical factors making it a complex, multi-criteria decision-making problem [9].

In this context, traditional single-criterion approaches are inadequate for capturing the full spectrum of variables influencing energy planning. There is a growing need for systematic, structured decision-support tools that can guide policymakers and stakeholders in evaluating multiple alternatives based on a set of interrelated criteria [10]. The Analytic Hierarchy Process (AHP), developed by Saaty, is one such multi-criteria decision analysis (MCDA) technique that facilitates the prioritization of alternatives through pairwise comparisons and consistency validation [11]. This study, therefore, applies AHP to evaluate and rank the most viable renewable energy technologies for decarbonization in Nigeria. The specific objectives are to (i) identify and structure decision criteria relevant to Nigeria's energy transition, (ii) apply the AHP framework to determine the relative importance of these criteria, and (iii) prioritize renewable energy alternatives accordingly. Integrating AHP and GIS enhances energy planning [12], supports wind deployment [13], and informs industrial safety decisions [14].

By leveraging AHP, the study provides a transparent and reproducible decision-support framework to inform policy formulation, investment planning, and strategic deployment of low-carbon technologies tailored to Nigeria's development goals. AHP-GIS integration improves renewable energy site selection in Nigeria, supporting sustainable development through informed decision-making [15][16][17].

II. METHODS

A. *Material and Methods*

This study employs the Analytic Hierarchy Process (AHP) to evaluate five renewable energy technologies in Nigeria: solar photovoltaic (PV), wind, biomass, hydropower, and geothermal energy. Data were sourced from the International Renewable Energy Agency (IRENA) [18], the Energy Commission of Nigeria (ECN), and the National Bureau of Statistics (NBS) [19]. IRENA provided global datasets on resource potential, installed capacity, and energy costs. contributed Nigeria-specific data on solar irradiance, wind speeds, biomass feedstock, hydropower sites, and geothermal gradients. NBS supplied socio-economic data such as agricultural waste generation and household energy use. These datasets were used to develop pairwise comparisons and derive priority rankings in the AHP model, ensuring technical accuracy and contextual relevance. Literature findings were validated through AHP-based questionnaires completed by 12 experts across energy, environment, and policy sectors. Their inputs ensured context-specific weighting of criteria and ranking of renewable technologies.

B. *Analytic Hierarchy Process (AHP) formulation.*

The Analytic Hierarchy Process (AHP) is distinguished by its decomposition of the decision problem into a hierarchical structure and the use of pairwise comparisons to evaluate factors and options [20]. Accordingly, the hierarchical model of the multi-criteria decision-making problem was developed using the AHP approach, organized into distinct levels objective, evaluation criteria, and available alternatives, as illustrated in Figure 1. These technologies represent the most feasible and contextually relevant options for Nigeria,[21] considering its geographic, climatic, and developmental characteristics. The Analytic Hierarchy Process (AHP) will be used to prioritize these alternatives based on their performance across the selected criteria (Fig.2). To effectively evaluate renewable energy technologies for decarbonization in Nigeria, five decision criteria were selected based on literature review and expert consultation. These criteria reflect the technical, economic, environmental, and social factors relevant to energy planning (Figure.2).

The AHP process involves several key steps [11]: first, the decision issue is broken down into a hierarchical structure, as illustrated in Figure 1; next, input on the relative importance of the decision elements is collected through pairwise comparisons; finally, the criteria are evaluated in pairs, and a normalized matrix is generated using Equations (1) and (4).

Table 1: Pairwise Comparison Matrix for Criteria

Criteria	*Cost*	*CO₂ Reduction*	*Availability*	*Maintenance*	*Social Acceptance*	
Cost	*1*	*1/3*	*1/2*	*2*	*3*	*1*
CO₂ Reduction	*3*	*1*	*2*	*4*	*5*	*3*
Availability	*2*	*1/2*	*1*	*3*	*4*	*2*
Maintenance	*1/2*	*1/4*	*1/3*	*1*	*2*	*1/2*
Social Acceptance	*1/3*	*1/5*	*1/4*	*1/2*	*1*	*1/3*

$$\overline{a_{ij}} = \frac{a_{ij}}{\sum_i a_{ij}} \qquad \textbf{(1)}$$

$$w_i = \left(\prod_{j=1}^{n} \overline{a_{ij}}\right)^{\frac{1}{n}} \qquad \textbf{(2)}$$

The value of n_{max} is computed from equation 3.28 as shown, reflect the technical, economic, environmental, and social factors relevant to energy planning (Figure.2):

$$\sum_{j=1}^{n}\left(\sum_{j=1}^{n} a_{ij}\,\dot{w}_j\right) = n_{max}\sum_{j=1}^{n}\dot{w} \quad =n_{max} \qquad \textbf{(3)}$$

Consistency ratio CR= CR=$\frac{CI}{RI}$

Where, CI= Consistency index of A given as $\frac{n_{max}-n}{n-1}$

And RI = Random Consistency Index of A is determined empirically. If CI ≤ 0.1, then consistency is acceptable.

The geometric mean is computed using n^{th} root

$$GM = \sqrt[n]{\left(\prod_{j=1}^{n} a_{ij}\right)} \qquad \textbf{(4)}$$

III. RESULTS AND DISCUSSIONS

A. Results comparison for the Criteria.

Table 1 presents the Pairwise Comparison Matrix for Criteria. The results show CO₂ Emission Reduction (41.6%) ranks highest, emphasizing Nigeria's climate priorities and emission goals. Availability follows (26.2%), reflecting the need for reliable, accessible resources across diverse regions. Cost (16.1%) is important but secondary to environmental and resource concerns, especially with potential external funding. Maintenance (9.9%) is considered manageable, favoring technologies with lower upkeep needs. Social Acceptance (6.2%) ranks lowest, suggesting limited current focus, though it remains vital for long-term project success in local communities. The values reflect expert judgment regarding the relative importance of each criterion.

Table 2 shows the final AHP rankings of renewable energy technologies based on weighted criteria. Geothermal ranks 1st (0.241), favored for its strong CO₂ reduction and reliability. Wind follows 2nd (0.226), driven by its availability and emission benefits, especially in northern Nigeria. Solar PV is 3rd (0.203), valued for resource abundance and cost, but limited by maintenance and social factors. Biomass (0.172) and Hydropower (0.158) rank 4th and 5th, reflecting challenges related to environmental concerns, variability, and possible social opposition.

Table 3 shows the **relative performance scores** of each renewable energy alternative, likely based on a single dominant criterion (e.g., CO₂ emission reduction) or a recalculated priority structure. **Geothermal** scores highest **(0.255),** confirming it as the strongest technology in emission reduction and overall contribution to decarbonization goals. **Wind** ranks second **(0.222)** with solid potential in terms of clean energy delivery and growing applicability in northern Nigeria. **Solar PV** follows closely in third **(0.195),** reflecting its environmental benefits and wide-scale deployment potential. **Biomass (0.165)** and **Hydropower (0.153)** trail behind, likely due to their lower performance in key environmental or efficiency metrics, including lifecycle emissions and resource reliability

Table 4 presents updated or scenario-adjusted scores for each renewable energy technology, reflecting how they perform under a specific analytical model or planning context (e.g., environmental policy emphasis, investor-driven preferences, or technical reassessment). The interpretation of the values is as follows: Geothermal scores highest at 0.269, further reinforcing its status as the top-performing renewable option in Nigeria. This indicates a favorable balance of environmental impact, resource availability, and operational suitability. Wind retains its position as a strong contender, scoring 0.223, reflecting its scalability and resource potential in regions like northern Nigeria. Solar PV, at 0.193, remains a highly relevant technology, valued for its wide geographic applicability, though slightly penalized possibly due to maintenance or cost factors in this model. Biomass and Hydropower again rank lower (0.166 and 0.149, respectively), likely due to challenges such as feedstock logistics, environmental concerns (e.g., deforestation), or community displacement issues associated with large dams

B. *Overall Ranking and Sensitivity analysis*

Table 5 shows the overall ranking of the renewable alternatives. Geothermal emerges as the most favorable renewable energy source, with a total score of 0.87. This is largely due to its high CO_2 emission reduction potential (0.30) and solid availability (0.25). Wind follows closely with a score of 0.84, benefitting from its high availability (0.28) and moderate CO_2 emission reduction potential (0.11). Solar PV ranks third, with a slightly higher score for cost (0.13), but slightly lower performance in CO_2 reduction (0.27) and availability (0.22). Biomass and hydropower scored (0.75) and (0.72), with biomass performing in cost (0.12), but lower in CO_2 reduction potential (0.20). Hydropower, despite good CO_2 reduction potential (0.21), scores lower in availability (0.10) and maintenance (0.11).

Table 6 show the impact of increasing the weight of the dominant criterion CO_2 emission reduction by 10%. The results show that Geothermal Energy gained the most from the increased weight of CO_2 emission reduction, with its score rising from 0.241 to 0.255 about 1.4 %. This confirms that geothermal is the most responsive and best-aligned with Nigeria's decarbonization goals, making it a highly robust and strategic choice under climate-focused energy policies. Wind Energy: Slight decrease (–0.004) suggests that while wind performs well overall, it is less dominant in emission reduction compared to geothermal. Still remains second-ranked, indicating stability in its strategic value. Solar PV drops by 0.008, showing greater sensitivity to the increased emphasis on CO_2 reduction. This reflects that although solar is abundant and cost-competitive, its lifecycle emissions or capacity factor may be lower than geothermal or wind, affecting its comparative score under stricter climate priorities. Biomass and Hydropower: Both alternatives saw decreases of –0.007 and –0.005, respectively. Their lower emissions performance, coupled with other drawbacks (e.g., resource variability, social impact), make them less favorable when emission reduction is prioritized.

In Figure 3, the decision-makers prioritized environmental impact (CO_2 emission reduction) as the highest-ranking criterion, indicating a strong preference for sustainability. Operational aspects such as availability and cost followed in importance, while social acceptance carried the least weight. In Figure 4, geothermal energy is considered the most favorable alternative based on the established criteria, primarily due to its low emissions and reliability. Despite being a long-established energy source, hydropower scores lowest, likely because of its associated environmental and social drawbacks. The bar graph in Figure 5 compares the original AHP scores of renewable energy alternatives with their revised scores after increasing the weight of CO_2 emission reduction by 10%. Geothermal and wind energy continue to hold high rankings, indicating the robustness of their preferred status even under increased emphasis on environmental concerns. Finally, Figure 6 reinforces the findings from Figure 2, adding clarity by presenting the ordinal ranks of the alternatives rather than just their numerical scores

Table 2: Criteria Weights (Priority Vector)

Criteria	*Priority vector*	*Rank*	*Consistency Check*
CO_2 Emission Reduction	*0.416*	*1*	$\lambda_{max} = 5.068$
Availability	*0.262*	*2*	*Consistency Index (CI) = 0.0171*
Cost	*0.161*	*3*	*Consistency Ratio (CR) = 0.0153*
Maintenance	*0.099*	*4*	*Since CR < 0.10, the judgments are consistent and acceptable*
Social Acceptance	*0.062*	*5*	

Table 3: Pairwise Comparison Matrix for Alternatives

Alternatives	*Solar*	*PV*	*wind*	*Biomass*	*Hydro*	*Geothermal*
Solar PV	1	1/2	3	2	1/3	1
Wind	2	1	4	3	1/2	2
Biomass	1/3	1/4	1	1/2	1/5	1/3
Hydropower	1/2	1/3	2	1	1/4	1/2
Geothermal	3	2	5	4	1	3

Table 4: Mean Priority Scores of Renewable Energy Alternatives and Rank

Alternatives	*Priority Vector*	*Rank*
Geothermal	*0.241(Highest priority)*	*1*
Wind	*0.226*	*2*
Solar PV	*0.203*	*3*
Biomass	*0.172*	*4*
Hydropower	*0.158*	*5*

Table 5: Overall Ranking of the renewable energy alternatives

Renewable Energy	**CO_2 Emission Reduction**	**Availability**	**Cost**	**Maintenance**	**Social Acceptance**	**Total Score**
Geothermal	0.30	0.25	0.12	0.10	0.10	0.87
Wind	0.28	0.24	0.11	0.10	0.10	0.84
Solar PV	0.27	0.22	0.13	0.1	0.1	0.82
Biomass	0.2	0.20	0.12	0.11	0.12	0.75
Hydropower	0.21	0.20	0.10	0.11	0.10	0.72

Table 6: Impact of increasing the weight of the dominant criterion CO_2 emission reduction by 10%:

Alternative	Original Score	New Score (+10% CO_2 Weight)	Change
Geothermal	0.241	0.255	+0.014
Wind	0.226	0.222	–0.004
Solar PV	0.203	0.195	–0.008
Biomass	0.172	0.165	–0.007
Hydropower	0.158	0.153	–0.005

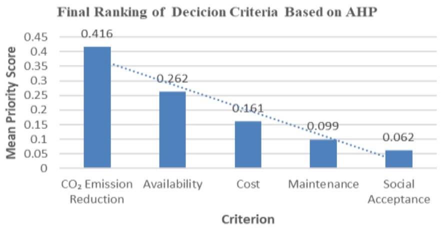

Figure 3: AHP-Derived Weights of Criteria

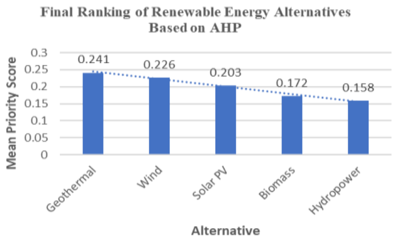

Figure 4: AHP-Derived Weights of Alternatives

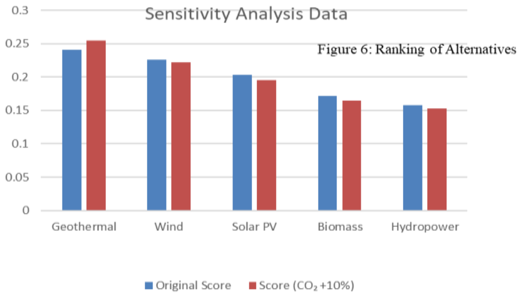

Figure 5: Sensitivity Analysis of Alternatives

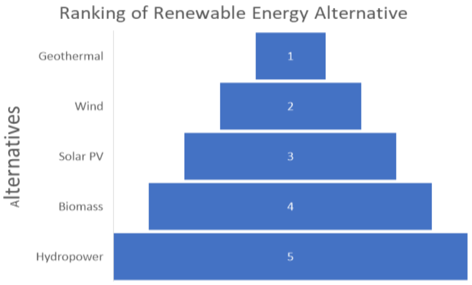

Figure 6: Ranking of Alternatives

V. CONCLUSION

The AHP analysis indicates that geothermal energy is the most suitable renewable energy option for Nigeria, with a priority score of 0.241, primarily due to its high CO_2 emission reduction potential. This was followed by wind energy (0.226) and solar PV (0.203), with both technologies benefiting from widespread resource availability and scalability. Biomass (0.172) and hydropower (0.158) ranked lower, owing to their relatively weaker performance in emission reduction and resource availability. The consistency ratio of the pairwise comparison matrix was calculated at 0.0153, confirming the reliability of the judgments made. The sensitivity analysis demonstrated that even with a 10% increase in CO_2 emission reduction weight, geothermal remained the top choice, showing a minor increase in score (0.014). These results suggest that Nigeria should prioritize geothermal resource development while also supporting wind and solar PV in suitable regions. The study's findings underscore the need for a diversified energy strategy, with future research focusing on the integration of fuzzy AHP or hybrid models to improve decision robustness, especially under uncertainty.

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