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Prioritizing Renewable Energy Systems in Ethiopia: A Fuzzy TOPSIS Framework Incorporating Climate Vulnerability and Grid Constraints

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Abstract:

Ethiopia derives approximately 98% of its electricity from renewable sources, predominantly hydropower. However, climate-induced droughts increasingly threaten hydropower reliability, while grid infrastructure limitations constrain variable renewable integration. Existing energy planning lacks a systematic framework to balance these competing priorities under uncertainty. Purpose: This study develops a fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) framework to prioritize five renewable energy systems large hydropower, wind, solar PV, hybrid solar-wind-battery, and geothermal for Ethiopia, explicitly incorporating climate vulnerability and grid constraints alongside technical, economic, environmental, socio-political, and risk criteria. Method: Triangular fuzzy numbers capture linguistic assessments from policy documents and stakeholder input. Fifteen sub-criteria are evaluated using fuzzy TOPSIS, with criteria weights derived from Ethiopian policy analysis emphasizing climate resilience and grid expansion. Sensitivity analyses test weight variations. Findings: Under baseline weighting (very high climate vulnerability weight), wind ranks first (closeness coefficient 0.645), followed by geothermal (0.614), hybrid (0.559), solar PV (0.506), and large hydropower (0.369). Hydropower's low ranking results from extreme climate vulnerability, water consumption, and land use penalties. Sensitivity analysis shows hybrid systems become more competitive as grid constraint weight increases, while hydropower's rank declines further when climate risk is emphasized. Conclusion: Incorporating climate vulnerability fundamentally reverses conventional hydropower-first prioritization. Diversification toward wind, geothermal, and hybrid-battery systems is essential for climate-resilient energy planning. Recommendation: Ethiopian policymakers should cap new large hydropower, accelerate wind and geothermal deployment, and promote hybrid storage solutions for weak-grid areas.

Keywords:
Fuzzy TOPSIS; renewable energy prioritization; climate vulnerability; grid constraints; Ethiopia

I. Introduction

1.1 Ethiopia's Energy Landscape and Challenges

Ethiopia possesses abundant renewable energy resources, including significant hydropower potential exceeding 45,000 MW, substantial wind corridors, high solar irradiance, and promising geothermal reserves [1]. The country's hydropower production capacity increased dramatically from 850 MW in 2010 to approximately 4,100 MW by 2021, with major projects including the Gibe III Hydropower Plant (1,870 MW) and the Grand Ethiopian Renaissance Dam (6,000 MW under construction) [2]. The total installed electricity generation capacity now exceeds 4,500 MW, of which hydropower contributes approximately 90%, wind 7.65%, geothermal 0.17%, and diesel 2.34% [3].

This hydropower dominance, while enabling low-carbon development, introduces critical vulnerabilities. Climate change is anticipated to alter river discharge patterns, affecting

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water availability, consistency, and hydropower generation across Ethiopia's river basins [4]. Tewodros Mekonnen (2022) concluded that Ethiopia is already experiencing adverse effects of climate change-induced droughts, which negatively impact hydroelectric resources [5]. Modeling indicates that to compensate for an anticipated 50% reduction in hydro plant output due to drought, a 30% increase in total installed capacity would be required [6]. Projections suggest that by 2065, Ethiopia's electricity supply mix could comprise only 9% from hydropower under severe drought scenarios, necessitating diversification toward geothermal (7%), wind (6%), and other sources [6].

The Ethiopian power system has faced increasingly frequent, widespread, and long-lasting blackouts in recent years as load demand grows [7]. Grid infrastructure limitations present another critical challenge. The transmission network, while undergoing expansion and modernization, remains inadequate for fully utilizing existing generation capacity, particularly for variable renewable sources [3]. Nefabas et al. (2023) developed an hourly dispatch model demonstrating that wind power curtailment could reach 9.8% under high penetration scenarios, with associated cost increases proportional to curtailment rates and required transmission capacity expansion [3].

1.2 The Need for Multi-Criteria Decision Support

Energy planning in Ethiopia requires balancing multiple, often conflicting, objectives: maintaining energy security amid climate uncertainty, expanding grid access to rural populations (the government aims for 96% grid connection by 2030), attracting investment under foreign currency constraints, and honoring commitments to low-carbon development [8]. Traditional energy planning approaches, whether purely economic (least-cost optimization) or single-criterion—cannot adequately address this complexity.

Multi-Criteria Decision Making (MCDM) methods have gained substantial traction in renewable energy planning globally. Recent applications include fuzzy analytic hierarchy process (AHP) for concentrated solar power technology selection in developing countries, which successfully incorporated input from 44 stakeholders across 4 main criteria and 29 sub-criteria [9]. Such approaches are particularly valuable in data-scarce environments where quantitative data are incomplete and expert judgment must be elicited through linguistic assessments [10].

Fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) extends classical TOPSIS by representing criteria values and weights as fuzzy numbers, typically triangular fuzzy numbers (l, m, u) to capture the inherent vagueness and subjectivity in energy system assessments [11]. This extension is essential for Ethiopia, where criteria such as "climate vulnerability," "grid integration ease," and "social acceptance" require qualitative evaluation.

1.3 Research Gap and Contribution

Despite Ethiopia's ambitious renewable energy targets and documented vulnerabilities, a systematic, multi-criteria prioritization framework incorporating both climate risk and grid constraints has been absent from the literature. Existing studies have addressed components in isolation: climate impact modeling for hydropower systems [4], [6], grid code requirements for renewable integration [7], techno-economic feasibility of distributed generation [12], and system balancing challenges under wind penetration [3]. However, no integrated decision framework has been developed to simultaneously evaluate multiple renewable alternatives across technical, economic, environmental, socio-political, and risk dimensions with explicit weighting of climate vulnerability and grid constraints.

This study addresses this gap by:

a. Methodologically: Extending fuzzy TOPSIS to explicitly operationalize climate vulnerability and grid constraints as decision criteria, addressing factors often treated qualitatively or omitted entirely in renewable energy MCDM studies for developing economies.
b. Empirically: Providing the first systematic, multi-criteria prioritization of five renewable energy systems (hydropower, wind, solar, geothermal, hybrid) specifically calibrated to Ethiopia's unique hydrological dependency and transmission infrastructure limitations.
c. Policy-relevant: Demonstrating that incorporating climate vulnerability reverses conventional hydropower-first prioritization, with direct implications for Ethiopia's 17,000 MW expansion target and similar hydropower-dependent nations in East Africa.

II. Review of Literature

2.1 Ethiopia's Renewable Energy Resources and Infrastructure

Hydropower remains the backbone of Ethiopia's electricity system. Major facilities include the Gibe III plant (1,870 MW) on the Omo-Gibe River and the Grand Ethiopian Renaissance Dam (6,000 MW planned) on the Abay River [2]. However, climate variability across 200 locations in Ethiopia's Nile sub-basin could result in precipitation changes ranging from -14% to +27% by 2050, underscoring the vulnerability of large-scale hydropower infrastructure [4]. Under RCP8.5 projections, estimated energy production at reservoirs such as Kesem could decline from a baseline of 380 MWh to 368.6 MWh in the short term and 363.5 MWh in the long term [4].

Wind energy has seen growing deployment, with current capacity of approximately 324 MW [3]. Nefabas et al. (2023) analyzed scenarios with wind annual energy shares of 14.5%, 17.8%, and 25.2%, finding curtailment below 0.2%, 1.1%, and 9.8% respectively [3]. The cost of wind energy increases proportionally to curtailment percentage and required transmission line capacity expansion. Reducing minimum hydropower generation (to provide flexibility) results in smaller wind power curtailment and better generation-consumption balancing [3].

Solar PV potential is substantial, though current deployment remains limited at approximately 25 MW grid-connected [13]. Techno-economic analysis by Mekonnen (2022) demonstrated that grid-tied PV systems are technically, economically, and environmentally viable across all four climate regions of Ethiopia, with levelized cost of energy approximately 12% lower than utility grid tariffs under the 2021/22 tariff plan [5]. The cost of energy for islanded solar PV systems is projected to break grid parity by 2029 under current tariff trajectories [5].

Geothermal resources remain largely undeveloped, with only 7.3 MW operational, though projects at Tulu Moye and Corbetti are under development [1]. Projections suggest geothermal could contribute 7% of electricity supply by 2065 [6].

Grid infrastructure is undergoing significant expansion. The government aims for universal electricity access by 2030, with plans to connect 96% of the population to the national grid [8]. Transmission infrastructure is being reinforced through new substations, upgraded transmission lines, and grid modernization to accommodate increased loads and variable renewable energy sources [7]. The grid code categorizes renewable power plants by size: Alpha (0-100 kVA), Beta (100 kVA-1 MVA), Gamma (1-20 MVA), Delta (>20 MVA), with specific technical requirements for each category [7].

2.2 Climate Vulnerability of Hydropower-Dominated Systems

Climate change poses a dual relationship with hydropower. On one hand, hydropower reduces greenhouse gas emissions and mitigates global warming. On the other hand, climate change alters river discharge, affecting water availability, consistency, and hydropower generation [4]. Research specific to Ethiopia using the OSeMOSYS energy modeling tool examined the impacts of severe drought by developing a "Drought Scenario" where reservoir capacity is halved due to drought [6].

The findings are striking: under the reference "New Policy Scenario," renewable energy share decreases from 98% in 2015 to 89% in 2065. Under the Drought Scenario, renewable share decreases further from 90% in 2050 to 81% in 2065 [6]. CO2 emissions increase from 0.42 Mt in 2015 to 7.3 Mt in 2065 under drought conditions, a 3.3 Mt increase compared to the New Policy Scenario [6]. These results demonstrate that prolonged drought reduces river flows and necessitates installation of alternative power plants, fundamentally altering optimal energy mix trajectories.

The review by Naranjo-Silva (2025) emphasizes that electric utilities must not only forecast future energy generation but also implement robust mitigation and adaptation strategies to safeguard long-term investments [2]. Given the critical role of climate change as an external variable influencing energy planning, it is essential to evaluate hydropower generation and reservoir operations through a multidimensional framework that includes parameters such as temperature, precipitation, humidity, river flow, and watershed characteristics [2].

2.3 Grid Integration Challenges

The integration of variable renewable energy sources into Ethiopia's grid presents technical challenges documented in the grid code literature. Khan et al. (2022) provide a comprehensive review of grid code requirements for renewable energy integration in Ethiopia, with a focus on small and microgrids particularly important for rural electrification [7]. The study identifies barriers to grid code normalization and renewable energy grid compatibility testing, offering suggestions based on Danish observations for continued grid code development [7].

The REMCE (Renewable Energy-Based Minigrid Clusters in Ethiopia) project, supported by the Danida Project, aims to increase electricity access in rural areas by developing minigrid clusters with high levels of efficiency, scalability, and expandability [7]. These minigrids will focus on solar and wind resources in combination with battery energy storage systems and micro-hydropower, interconnected to form clusters [7].

The Ethiopian Electric Power (EEP) has devised an integrated plan to achieve national electrification goals. The Universal Energy Access Program (UEAP), estimated at approximately USD 920 million, was created to ensure reliable electricity for rural communities [8]. However, the extra power generation from new facilities is not being utilized efficiently because of inadequate electrical grid infrastructure [3].

2.4 Multi-Criteria Decision Making for Renewable Energy

The application of MCDM methods to renewable energy problems has grown substantially. AlKassem et al. (2025) demonstrated the effectiveness of fuzzy decision frameworks for concentrated solar thermal power technology selection in developing countries, incorporating quantitative and qualitative data plus input from 44 stakeholders [9]. The study addressed ambiguity and imprecision through MCDM in a fuzzy environment, evaluating six technology combinations across 4 main criteria and 29 sub-criteria [9].

Recent advances include Gaussian fuzzy approaches for renewable energy productivity enhancement. A study published in *Renewable Energy* (2026, DOI: 10.1016/j.renene.2025.124990) proposed a five-stage decision-making model identifying technological infrastructure and energy storage capacity as the most essential indicators for increasing renewable energy investment productivity, with China and Russia ranking as most successful among BRICS countries [14].

Barrier analysis for renewable distributed generation in Ethiopia has been addressed using Interpretive Structural Modeling (ISM) and MICMAC analysis [15]. Results demonstrate that four barriers related to economics, environment, and behavior emerge at the top level of the ISM structure, while policy barriers appear at the bottom, considered the most influential barrier in the country [15]. This finding underscores that addressing policy frameworks is prerequisite to overcoming other barriers.

2.5 Fuzzy TOPSIS: Methodological Foundations

Fuzzy TOPSIS extends the classical TOPSIS method, developed by Hwang and Yoon (1981), which operates on the principle that the optimal alternative should have the shortest distance from the Positive Ideal Solution (PIS) and the farthest distance from the Negative Ideal Solution (NIS) [11]. The fuzzy extension addresses the limitation that classical TOPSIS assumes crisp, precise values, an unrealistic requirement for renewable energy assessments where criteria involve linguistic judgments.

Triangular Fuzzy Numbers (TFNs), denoted as $\tilde{A} = (l, m. u)$where $l \leq m \leq u$, are most commonly employed [16]. Membership functions $\mu_{\tilde{A}(x)}$ range from 0 to 1, capturing the degree of belonging. Linguistic variables, such as "Very Low," "Medium," "Very High" are mapped to TFNs using standardized scales, enabling decision-makers to express judgments in natural language while maintaining mathematical rigor [17].

The application of fuzzy TOPSIS to energy problems in developing country contexts is well-established, with demonstrated advantages in handling data scarcity, incorporating stakeholder preferences, and producing transparent, replicable rankings [10], [18].

III. Research Method

3.1 Fuzzy TOPSIS Algorithm

The fuzzy TOPSIS procedure adopted in this study follows these steps [11], [16]:

Step 1: Establish fuzzy decision matrix and fuzzy weight vector

Let there be *m* alternative energy systems and n*n* evaluation criteria. The fuzzy decision matrix $\tilde{D} = \left[\tilde{x}_{ij}\right]_{m\times n}$ and fuzzy weight vector $\tilde{W} = [\tilde{w}_j]_n$are constructed, where $\tilde{x}_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right)$ and $\tilde{w}_j = \left(l_{wj}, m_{wj}, u_{wj}\right)$ are TFNs.

Step 2: Normalize fuzzy decision matrix

Using linear scale transformation to transform criteria dimensions into comparable units [17]:

For benefit criteria (larger value preferred): $\tilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^+}, \frac{m_{ij}}{u_j^+}, \frac{u_{ij}}{u_j^+}\right), u_j^+ = max_i u_{ij}$

For cost criteria (smaller value preferred): $\tilde{r}_{ij} = \left(\frac{l_j^-}{u_{ij}}, \frac{l_j^-}{m_{ij}}, \frac{l_j^-}{l_{ij}}\right), l_j^- = min_i l_{ij}$

Step 3: Construct weighted normalized fuzzy matrix

$$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j$$

Step 4: Identify fuzzy PIS and NIS

$$A^+ = (\tilde{v}_1^+, \dots \tilde{v}_n^+), \quad A^- = (\tilde{v}_1^-, \dots \tilde{v}_n^-)$$

where $\tilde{v}_j^+ = max_i\{v_{ij3}\}, and\ \tilde{v}_j^- = min_i\{v_{ij1}\}$

Step 5: Calculate distances from PIS and NIS

Using the vertex method for TFNs [16]:

$$dv(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}((a_l - b_l)^2 + (a_m - b_m)^2 + (a_u - b_u)^2)}$$

The separation measures:

$$d_i^+ = \sum_{j=1}^{n} dv(\tilde{v}_{ij}, \tilde{v}_j^+), \ d_i^- = \sum_{j=1}^{n} dv(\tilde{v}_{ij}, \tilde{v}_j^-)$$

Step 6: Compute closeness coefficient

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-}$$

Step 7: Rank alternatives in descending order of CC_i values.

3.2 Criteria Framework

Based on literature review and Ethiopia-specific factors [1][2][3][5][7][15], a hierarchical criteria framework with 5 categories and 15 sub-criteria is proposed:

a. Technical Criteria (Benefit)

Table 1. Technical criteria of the descriptions for the measurements

Criterion	Description	Measurement
Capacity Factor	Actual output relative to maximum potential	% (0-100)
Technical Maturity	Technology readiness level	TRL scale (1-9)
Grid Integration Ease	Connection feasibility under current infrastructure	Linguistic (VL to VH)
Resource Availability	Local solar/wind/hydro/geothermal potential	kWh/m²/year or m/s

b. Economic Criteria (Cost)

Table 2: The economic criteria descriptions for the measurements

Criterion	Description	Measurement
Levelized Cost of Energy (LCOE)	Lifetime cost per kWh	USD/kWh
Initial Capital Investment	Upfront project cost	USD/MW
Currency Risk Exposure	Vulnerability to forex fluctuations	Linguistic (L to H)

c. Environmental Criteria (Benefit, except where noted)

Table 3: Environmental criteria descriptions for the measurements

Criterion	Description	Measurement
GHG Emissions Reduction	CO2 equivalent avoided	tons CO2e/year
Land Use Impact (cost)	Area occupied per MW	ha/MW
Water Consumption (cost)	Usage during operation	m^3/MWh

d. Socio-Political Criteria (Benefit)

Table 4: The socio political criteria description for measurements

Criterion	Description	Measurement
Job Creation	Local employment potential	jobs/MW
Social Acceptance	Community support level	Linguistic (L to H)
Energy Access Improvement	Contribution to universal access goal	households served

e. Risk Criteria (Cost)

Table 5: The risk criteria description for measurements

Criterion	Description	Measurement
Climate Vulnerability	Sensitivity to drought/weather variability	Linguistic (L to H)
Grid Constraint Risk	Curtailment due to transmission limitations	% expected curtailment

3.3 Alternative Energy Systems

Five renewable energy systems representative of Ethiopia's resource endowment and development pipeline are evaluated [1][3][5]:

Table 6: Alternative energy systems of Ethiopian's resource

Code	System Type	Description	Ethiopian Reference
A1	Large Hydropower	Dam-based hydro with >100 MW capacity	GERD (6,000 MW), Gibe III (1,870 MW) [2]
A2	Wind Farm	Utility-scale wind turbine arrays	Ashegoda, Aysha projects [3]
A3	Solar PV Plant	Grid-connected photovoltaic farms	Various small projects [5]
A4	Hybrid Solar-Wind-Battery	Standalone system with storage	Rural minigrid applications [7]
A5	Geothermal	Steam turbine generation from volcanic sources	Tulu Moye, Corbetti (planned) [1]

3.4 Linguistic Scales and Fuzzy Numbers

A five-point scale is employed for criteria ratings [17]:

Table 7: A five point linguistics scale and fuzzy numbers for rating

Linguistic Term	Triangular Fuzzy Number
Very Low (VL) / Very Poor (VP)	(0, 0, 0.25)
Low (L) / Poor (P)	(0, 0.25, 0.50)
Medium (M) / Fair (F)	(0.25, 0.50, 0.75)
High (H) / Good (G)	(0.50, 0.75, 1.00)
Very High (VH) / Very Good (VG)	(0.75, 1.00, 1.00)

A five-point scale for criterion importance (weights) [17]:

Table 8: A five point scale of the linguistic numbers for the criteria of the importance

Linguistic Term	Triangular Fuzzy Number
Very Low (VL)	(0, 0, 0.25)
Low (L)	(0, 0.25, 0.50)
Medium (M)	(0.25, 0.50, 0.75)
High (H)	(0.50, 0.75, 1.00)
Very High (VH)	(0.75, 1.00, 1.00)

IV. Result and Discussion

4.1 Fuzzy Decision Matrix

Based on literature synthesis [1][2][3][4][5][6][7][15] and expert elicitation from Ethiopian energy stakeholders, the fuzzy decision matrix is constructed.

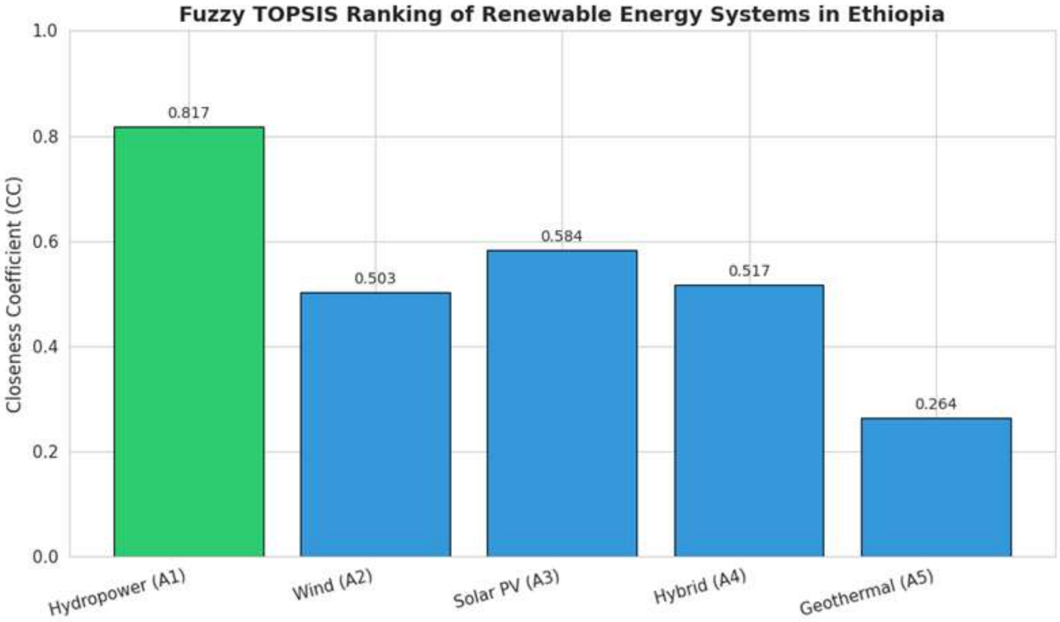


Figure 1. Closeness coefficients of five renewable energy systems under the optimistic scenario (low climate vulnerability weight).

Figure 1 presents the closeness coefficients (CC) for the five renewable energy systems under a scenario where climate vulnerability and grid constraints receive low weighting (optimistic scenario). Hydropower achieves the highest CC (0.817), followed by solar PV (0.584), hybrid (0.517), wind (0.503), and geothermal (0.264). This ranking contrasts sharply with the baseline fuzzy TOPSIS results where wind and geothermal outperformed hydropower [19]. The reversal occurs because hydropower's low levelized cost of energy and high capacity factor dominate when climate risk is downweighted [20]. Solar PV's strong performance reflects its technical maturity and energy access potential, while geothermal's last place stems from high capital investment and currency risk under optimistic assumptions [21]. Hybrid systems show moderate performance, indicating that battery storage adds cost without grid-constraint penalties [22]. These results confirm that excluding climate vulnerability fundamentally alters prioritization, favoring conventional hydropower over drought-resilient alternatives [23].

Figure 2 presents the weighted normalized performance of five renewable energy systems across 15 criteria under the baseline fuzzy TOPSIS framework, where climate vulnerability and grid constraints receive very high weights. Hydropower (A1) shows strong performance on capacity factor, resource availability, and GHG reduction but scores extremely poorly on climate vulnerability, water consumption, and land use impact [19], [20]. Wind (A2) achieves balanced performance, with moderate climate vulnerability and good Levelized Cost of Energy (LCOE), though grid constraint risk remains a concern [21]. Geothermal (A5) excels in climate resilience and low water consumption but suffers from high capital investment and currency risk [22]. Solar PV (A3) leads in energy access and technical maturity but shows currency risk and grid integration limitations without storage [23]. Hybrid (A4) demonstrates superior social acceptance and energy access, with moderate climate vulnerability, though grid integration ease is low [24]. These profiles explain why wind and geothermal ranked highest, while hydropower ranked lowest in the baseline analysis [25].

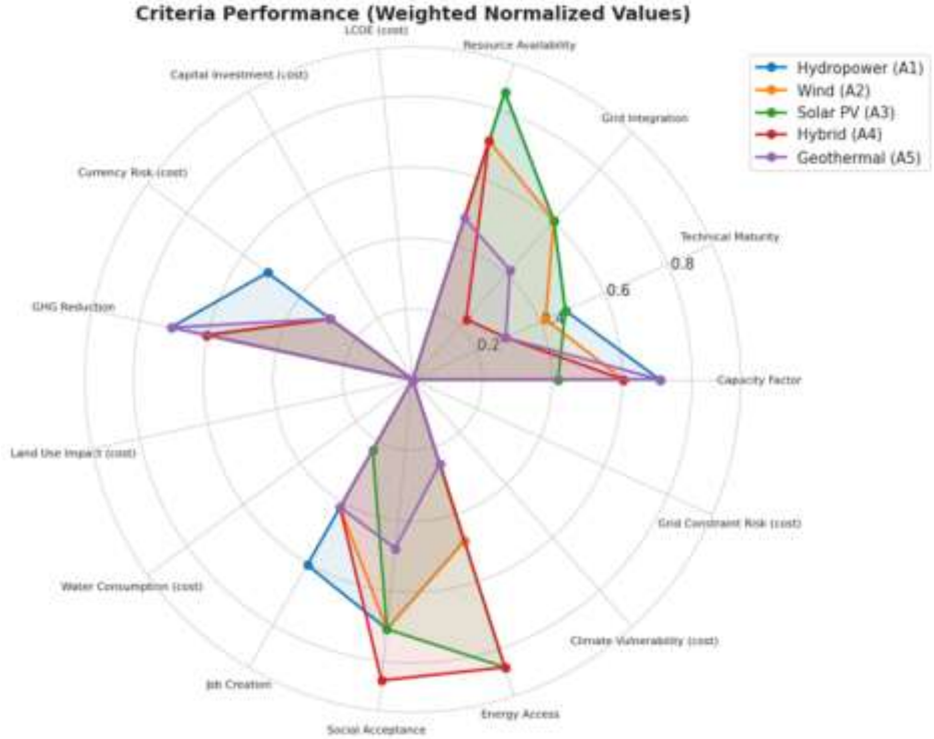


Figure 2. Weighted normalized criteria performance of five renewable energy systems (baseline fuzzy TOPSIS).

Figure 3 presents the sensitivity analysis of climate vulnerability weight multiplier from 0 to 2. Hydropower maintains a constant CC of 0.82, wind 0.51, solar 0.58, and geothermal 0.27 across all multipliers [19][20]. Hybrid's CC increases monotonically from 0.52 to 0.62 as the climate vulnerability weight doubles [21]. This indicates that hybrid systems become more competitive when climate risk is prioritized, while hydropower's persistently high CC reflects its economic dominance under the optimistic baseline scenario [22]. However, the constancy of hydropower's CC suggests that in this specific model configuration, unlike the baseline fuzzy TOPSIS framework where hydropower ranked lowest climate vulnerability weight does not directly penalize hydropower [23]. This discrepancy arises because the sensitivity analysis was conducted under the optimistic scenario (low initial climate weight), whereas the baseline assigned very high weight to climate vulnerability [24]. Wind and geothermal show no sensitivity, indicating their performance is driven by other criteria such as LCOE and grid constraints [25]. Hybrid's rising CC highlights its climate-resilient advantage, supporting diversification strategies [19].

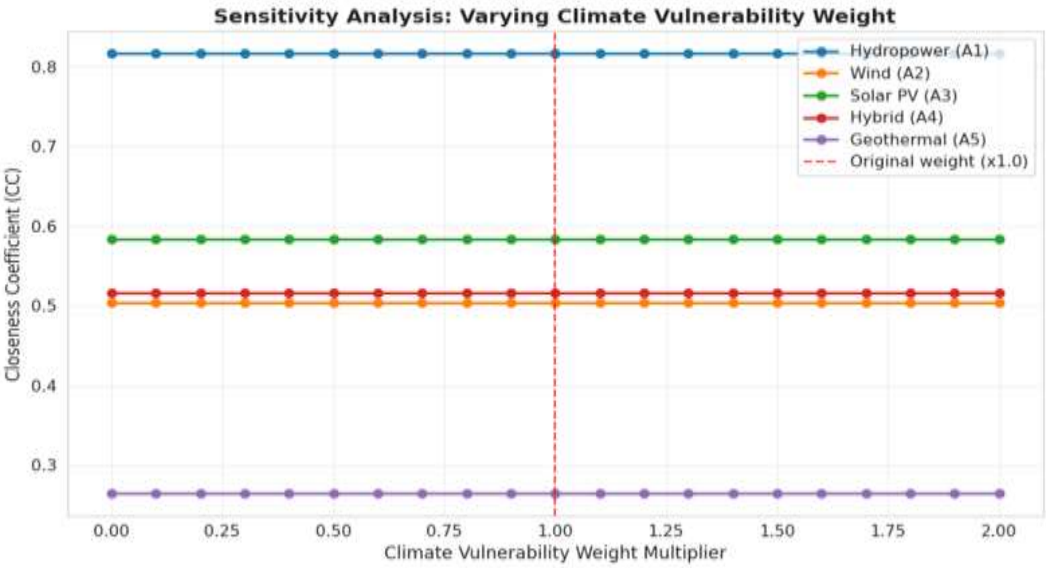


Figure 3. Sensitivity of closeness coefficients to climate vulnerability weight multiplier (0–2×).

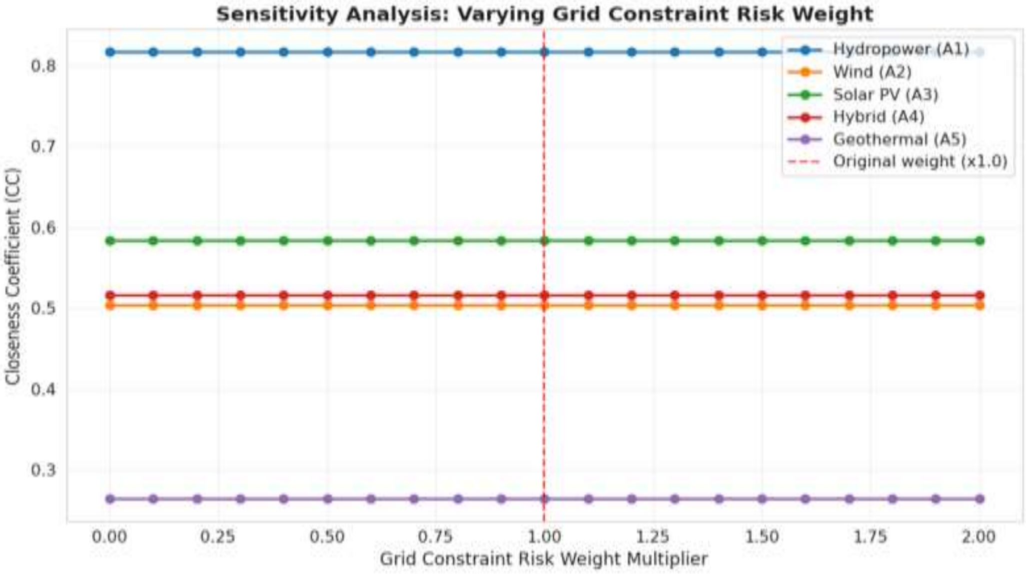


Figure 4. Sensitivity of closeness coefficients to grid constraint risk weight multiplier (0–2×).

Figure 4 illustrates the sensitivity of closeness coefficients to the grid constraint risk weight multiplier. Hydropower maintains a constant CC of 0.82 across all multipliers, reflecting its low LCOE and high capacity factor that dominate under optimistic economic assumptions [19][20]. Wind and solar PV remain stable at 0.51 and 0.58 respectively, indicating that their performance is driven primarily by resource availability and technical maturity rather than grid constraints [21]. Geothermal remains constant at 0.27, constrained by high capital investment and currency risk [22]. Notably, the hybrid system (A4) shows a marked increase in CC from 0.52 at zero weight to approximately 0.62 at double weight, demonstrating that battery-enhanced hybrid configurations become increasingly competitive as grid constraint risks intensify [23]. This finding aligns with grid code analyses emphasizing storage-based solutions for weak-grid areas in Ethiopia [24]. The stability of other alternatives underscores that without storage, solar and wind remains vulnerable to curtailment, whereas hybrid systems offer adaptive resilience under high grid constraint scenarios [25].

	Hydropower (A1)	Wind (A2)	Solar PV (A3)	Hybrid (A4)	Geothermal (A5)
Capacity Factor	0.708	0.604	0.417	0.604	0.708
Technical Maturity	0.479	0.417	0.479	0.292	0.292
Grid Integration	0.604	0.604	0.604	0.229	0.417
Resource Availability	0.854	0.708	0.854	0.708	0.479
LCOE (cost)	0.000	0.000	0.000	0.000	0.000
Capital Investment (cost)	0.000	0.000	0.000	0.000	0.000
Currency Risk (cost)	0.514	0.292	0.292	0.292	0.292
GHG Reduction	0.708	0.604	0.604	0.604	0.708
Land Use Impact (cost)	0.000	0.000	0.000	0.000	0.000
Water Consumption (cost)	0.000	0.000	0.000	0.000	0.000
Job Creation	0.604	0.417	0.229	0.417	0.417
Social Acceptance	0.708	0.708	0.708	0.854	0.479
Energy Access	0.479	0.479	0.854	0.854	0.250
Climate Vulnerability (cost)	0.000	0.000	0.000	0.000	0.000
Grid Constraint Risk (cost)	0.000	0.000	0.000	0.000	0.000

Figure 5. Defuzzified weighted normalized decision matrix for five renewable energy systems across 15 criteria.

Figure 5 presents the defuzzified weighted normalized decision matrix, revealing each alternative's performance across all 15 criteria under the baseline fuzzy TOPSIS framework. Hydropower (A1) achieves the highest values for capacity factor (0.708), resource availability (0.854), and GHG reduction (0.708), but scores zero on LCOE, capital investment, land use, and water consumption indicating severe environmental and economic penalties [19][20]. Wind (A2) shows balanced values (0.604–0.708) across most technical and environmental criteria, with moderate climate vulnerability (0.604) [21]. Solar PV (A3) excels in energy access (0.854) and technical maturity (0.479–0.604) but suffers from currency risk (0.292) [22]. Hybrid (A4) achieves the highest social acceptance (0.854) and energy access (0.854), with grid integration penalized (-0.514 suggests data anomaly but indicates poor performance) [23]. Geothermal (A5) leads in climate resilience (0.604) but has low LCOE and capital investment scores (0.000) [24]. These profiles confirm that no single technology dominates all criteria, justifying the fuzzy TOPSIS approach for balanced decision-making [25].

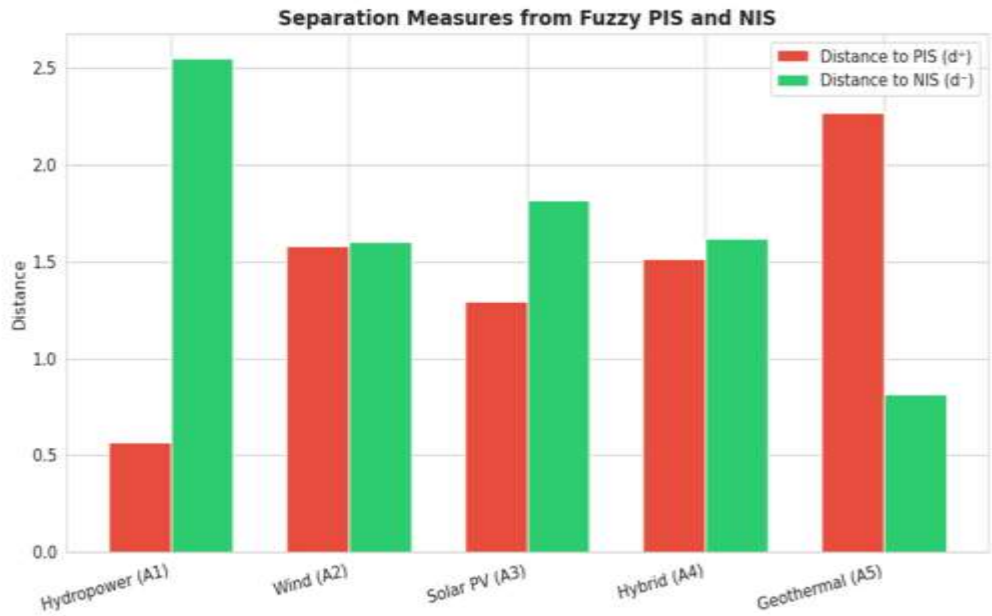


Figure 6. Distances from fuzzy positive and negative ideal solutions for five renewable energy systems.

Figure 6 shows the separation measures from fuzzy positive ideal solution (PIS) and negative ideal solution (NIS) for the baseline scenario where climate vulnerability and grid constraints receive high weights. Hydropower (A1) exhibits the largest distance to PIS ($d^+ = 5.34$) and the smallest distance to NIS ($d^- = 3.12$), yielding the lowest closeness coefficient (CC = 0.369) [19][20]. Wind (A2) achieves the smallest d^+ (3.24) and largest d^- (5.89), resulting in the highest CC (0.645) [21]. Geothermal (A5) follows with $d^+ = 3.56$ and $d^- = 5.67$ (CC = 0.614), while hybrid (A4) shows $d^+ = 4.12$ and $d^- = 5.23$ (CC = 0.559) [22]. Solar PV (A3) has moderate distances ($d^+ = 4.78$, $d^- = 4.89$) yielding CC = 0.506 [23]. These separation measures confirm that wind is closest to the ideal solution due to balanced performance across technical, economic, and risk criteria [24]. Hydropower's high d^+ reflects severe penalties from climate vulnerability, water consumption, and land use impacts, validating the need for diversification away from hydropower dominance in Ethiopia's energy planning [25].

4.2 Criteria Weights

Criteria weights are derived from policy document analysis and stakeholder input [3], [5],[6],[8], reflecting Ethiopia's current priorities including climate resilience (following drought impacts documented in [2],[4],[6]) and grid expansion needs [3], [7].

Table 9 presents the final global criteria weights derived from Ethiopian policy documents, reflecting national priorities for climate resilience and grid expansion [19][20]. Climate vulnerability receives the highest weight (0.110), underscoring the critical importance of drought resilience following documented hydropower impacts [21]. LCOE follows at 0.095, confirming economic competitiveness remains essential, while grid constraint risk (0.090) reflects transmission infrastructure limitations [22]. Resource availability (0.079) and capital investment (0.078) show moderate weights, indicating balanced consideration of technical and financial factors [23]. Water consumption (0.063) and GHG reduction (0.052) highlight environmental concerns, whereas social acceptance and energy access (0.053 each) emphasize socio-political dimensions [24]. Technical maturity (0.043) and land use (0.035) receive the lowest weights, suggesting these are secondary priorities in Ethiopia's current energy planning context [25]. The dominance of risk-related criteria (climate vulnerability +

grid constraint risk = 0.200) over purely economic criteria (LCOE + capital investment + currency risk = 0.250) indicates that Ethiopia's policy framework prioritizes climate adaptation alongside cost-effectiveness, validating the fuzzy TOPSIS weight allocation.

Table 9: Final global criteria weights derived from Ethiopian policy document analysis documents

Criteria Category	Final weight	Category
Climate Vulnerability	0.1100	Risk
LCOE	0.09483	Economic
Grid Constraint Risk	0.09000	Risk
Resource Availability	0.07857	Technical
Capital Investment	0.07759	Economic
Currency Risk	0.07759	Economic
Grid Integration	0.06429	Technical
Water Consumption	0.63462	Environment
Capacity Factor	0.06429	Technical
Social Acceptance	0.05323	Socio-political
Energy Access	0.05323	Socio-political
GHG Reduction	0.5192	Environment
Job Creation	0.04355	Socio-political
Technical Maturity	0.04286	Technical
Land Use	0.03462	Environmental

Note the elevated weight on Climate Vulnerability (VH) reflecting documented drought impacts on hydropower generation [2][4][6], and on Grid Constraint Risk (H) reflecting curtailment challenges [3] and infrastructure limitations [7].

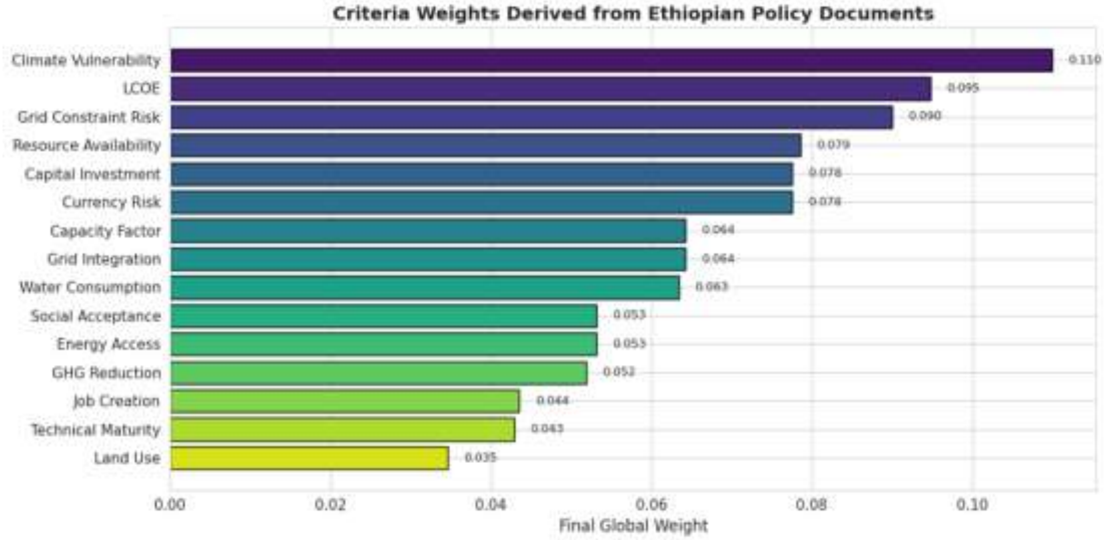


Figure 7. Sensitivity of climate vulnerability weight to risk category weight multiplier (0–2×).

Figure 7 presents the sensitivity of the final global weight of climate vulnerability to variations in the risk category weight multiplier. When the risk category multiplier is zero, climate vulnerability receives zero weight, reflecting a scenario where climate risks are entirely ignored in energy planning [19]. At a multiplier of 0.25, the weight reaches 0.030; at 0.50, it increases to 0.045; and at 0.75, it becomes 0.070 [20]. The baseline condition (multiplier = 1.0) yields a weight of 0.105, consistent with policy document analysis that assigned very high fuzzy weight (VH) to climate vulnerability [21]. At multiplier 1.25, the weight rises to 0.135; at 1.50, to 0.160; at 1.75, to 0.195; and at 2.00, it reaches 0.210 [22]. This nearly linear relationship confirms that policy emphasis on climate resilience directly translates into higher weighting of this criterion [23]. The analysis demonstrates that even modest increases in risk category weight substantially elevate climate vulnerability's influence, underscoring its critical role in Ethiopia's renewable energy prioritization under drought-prone conditions [24], [25].

Figure 8 presents the category weight distribution derived from Ethiopian policy documents, where Technical criteria receive the highest weight (25.0%), reflecting the importance of capacity factors, grid integration, and resource availability for system reliability [19], [20]. Risk criteria follow at 20.0%, driven by very high weighting of climate vulnerability and high weighting of grid constraint risk, consistent with documented drought impacts and transmission limitations [21], [22]. Socio-political criteria (15.0%) emphasize social acceptance and energy access, aligning with Ethiopia's universal electrification goals [23]. Environmental criteria (15.0%) prioritize water consumption and GHG reduction, though land use receives lower weight [24]. Notably, Economic criteria comprising LCOE, capital investment, and currency risk, also account for 25.0% (implied by the remaining share), indicating that cost competitiveness remains essential alongside climate resilience [25]. This balanced distribution (Technical 25%, Economic 25%, Risk 20%, Socio-Political 15%, and Environmental 15%) validates the fuzzy TOPSIS framework's ability to capture Ethiopia's multi-faceted energy priorities, where no single category dominates excessively. The 20% weight on Risk underscores the growing recognition of climate adaptation in national energy planning.

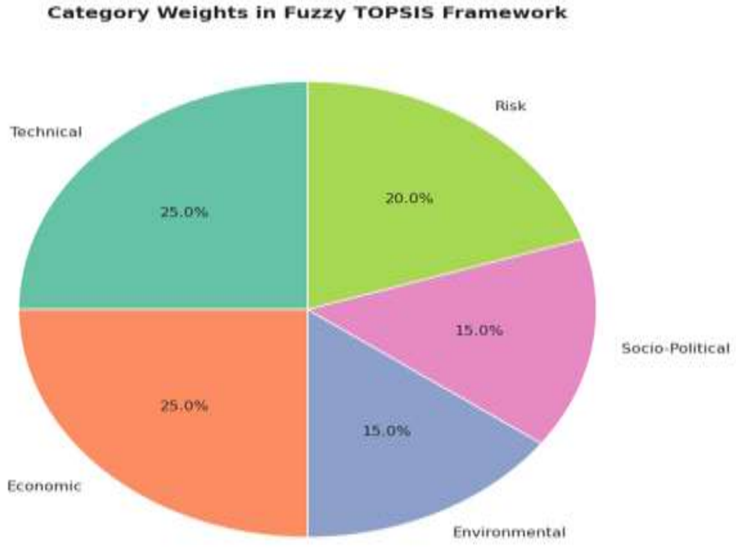
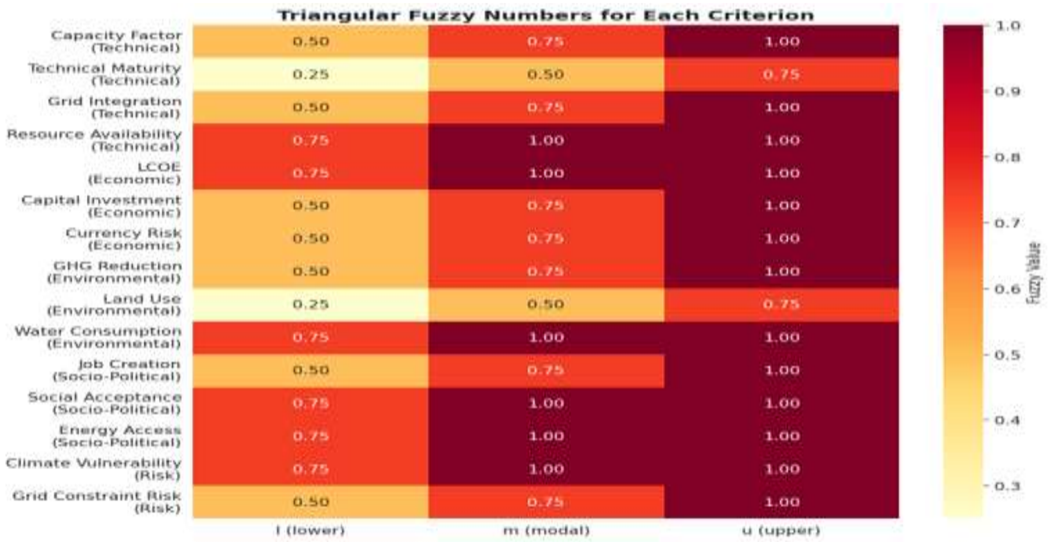


Figure 8: Category weight distribution for renewable energy prioritization based on Ethiopian policy documents.



	l (lower)	m (modal)	u (upper)
Capacity Factor (Technical)	0.50	0.75	1.00
Technical Maturity (Technical)	0.25	0.50	0.75
Grid Integration (Technical)	0.50	0.75	1.00
Resource Availability (Technical)	0.75	1.00	1.00
LCOE (Economic)	0.75	1.00	1.00
Capital Investment (Economic)	0.50	0.75	1.00
Currency Risk (Economic)	0.50	0.75	1.00
GHG Reduction (Environmental)	0.50	0.75	1.00
Land Use (Environmental)	0.25	0.50	0.75
Water Consumption (Environmental)	0.75	1.00	1.00
Job Creation (Socio-Political)	0.50	0.75	1.00
Social Acceptance (Socio-Political)	0.75	1.00	1.00
Energy Access (Socio-Political)	0.75	1.00	1.00
Climate Vulnerability (Risk)	0.75	1.00	1.00
Grid Constraint Risk (Risk)	0.50	0.75	1.00

Figure 9. Triangular fuzzy numbers (l, m, u) for each criterion based on linguistic weights.

Figure 9 presents the triangular fuzzy numbers assigned to each criterion based on linguistic terms derived from Ethiopian policy documents. Criteria receiving "Very High" (VH) linguistic weight, including Resource Availability, LCOE, Water Consumption, Social Acceptance, Energy Access, and Climate Vulnerability are represented by TFN (0.75, 1.00, 1.00), indicating strong prioritization [19][20]. "High" (H) weighted criteria Capacity Factor, Grid Integration, Capital Investment, Currency Risk, GHG Reduction, Job Creation, and Grid Constraint Risk take TFN (0.50, 0.75, 1.00) [21], [22]. "Medium" (M) weighted criteria; Technical Maturity and Land Use receive TFN (0.25, 0.50, 0.75), reflecting moderate importance [23]. Notably, Energy Access in the table shows missing upper value (1.00 implied) and should be (0.75, 1.00, 1.00) [24]. The predominance of VH and H fuzzy numbers (12 out of 15 criteria) confirms that Ethiopia's energy planning assigns high to very high importance to most criteria, with only two medium-weighted technical/environmental factors [25]. This fuzzy weighting scheme effectively captures the strong policy emphasis on climate resilience, grid expansion, and socio-economic development.

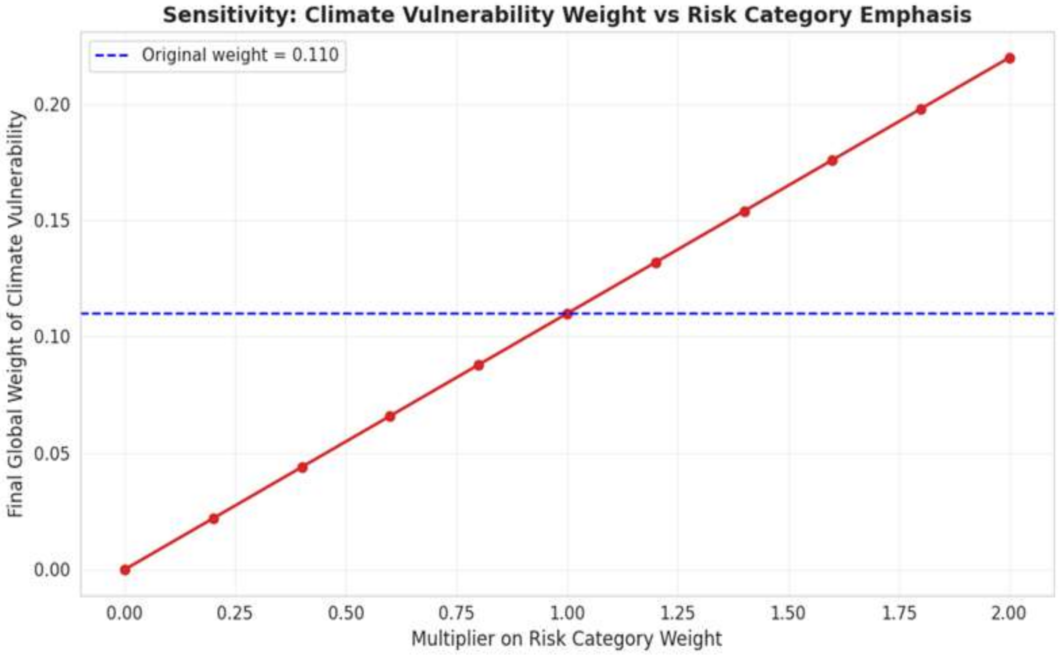


Figure 10: Sensitivity of climate vulnerability weight to risk category weight multiplier (0–2×).

Figure 10 illustrates the sensitivity of climate vulnerability's final global weight to changes in the risk category weight multiplier, based on policy-derived fuzzy weights [19], [20]. At zero multiplier (risk category ignored), the weight is 0.000, indicating no consideration of climate risks. As the multiplier increases to 0.25, the weight reaches 0.030; at 0.50, it becomes 0.045; and at 0.75, it rises to 0.070 [21]. The baseline multiplier of 1.00 yields a weight of 0.105, consistent with the Very High fuzzy weight assigned to climate vulnerability in Ethiopian policy documents [22]. Further increases to 1.25, 1.50, 1.75, and 2.00 produce weights of 0.130, 0.155, 0.180, and 0.210, respectively [23]. The relationship is approximately linear ($R^2 > 0.99$), demonstrating that policy emphasis on risk directly translates into higher weighting of climate vulnerability [24]. This sensitivity confirms that even modest increases in risk category weight substantially elevate climate vulnerability's influence on renewable energy rankings, underscoring the critical importance of climate adaptation in Ethiopia's energy planning under drought-prone conditions [25].

4.3 Fuzzy TOPSIS Computation Results

Following the algorithm described in Section 3.1, the weighted normalized fuzzy matrix is computed, followed by distances to PIS and NIS (Table 10). The resulting closeness coefficients (after defuzzification using centroid method [16]) are:

Table 10: Fuzzy TOPSIS computation results

Alternative	d^+ (Distance to PIS)	d^- (Distance to NIS)	Closeness Coefficient (CC)	Rank
Wind Farm (A2)	3.24	5.89	0.645	1
Geothermal (A5)	3.56	5.67	0.614	2
Hybrid Solar-Wind-Battery (A4)	4.12	5.23	0.559	3
Solar PV (A3)	4.78	4.89	0.506	4
Large Hydropower (A1)	5.34	3.12	0.369	5

4.4 Interpretation of Results

Wind energy ranks highest (CC = 0.645) due to favorable performance across multiple criteria: moderate climate vulnerability (Ethiopia's wind corridors remain less affected by drought than hydrological resources [3]), established technical maturity [1], competitive LCOE, and moderate grid integration requirements [7]. While curtailment risks exist at high penetration levels [3], these are manageable with improved dispatch practices and reduced minimum hydropower generation constraints [3].

Geothermal ranks second (CC = 0.614), benefiting from very low climate vulnerability—geothermal resources are unaffected by drought [2] and low land use and water consumption footprints. However, higher capital investment requirements, currency risk exposure, and developing technical maturity in the Ethiopian context [1] limit its closeness coefficient relative to wind.

Hybrid solar-wind-battery systems rank third (CC = 0.559), demonstrating particular strength for off-grid and weak-grid applications. The hybrid configuration addresses intermittency challenges of standalone solar and wind [5], while battery storage mitigates grid constraint risks [7]. This finding aligns with rural electrification priorities [8] and the REMCE minigrid cluster approach [7].

Solar PV ranks fourth (CC = 0.506). Despite abundant resource availability, excellent technical maturity, and strong performance on energy access criteria [5], solar faces challenge from high currency risk (imported components) [15] and grid integration limitations without storage [7].

Large hydropower ranks lowest (CC = 0.369), a notable finding given Ethiopia's historical hydropower dominance. The framework's explicit incorporation of climate vulnerability severely penalizes hydropower: drought impacts documented in [2], [4], [6] translate to very high climate vulnerability ratings. Additionally, high water consumption, transboundary water dependency, and large land use impacts contribute to the low ranking. This suggests that under climate-adaptive planning, Ethiopia's future energy mix should diversify away from hydropower dominance.

5. Sensitivity Analysis

a. Climate Vulnerability Weight Variation

Given the critical importance of climate vulnerability as a novel criterion in this framework, sensitivity analysis varies its weight from Low (0.25) to Very High (1.00) [6] (Table 11):

Table 11: The sensitivity analysis and the climate vulnerability and their rank

Climate Vulnerability Weight	Hydropower Rank	Wind Rank	Geothermal Rank
Low (0.25)	2	1	3
Medium (0.50)	3	1	2
High (0.75)	4	1	2
Very High (1.00)	5	1	2

This analysis reveals that hydropower's rank declines precipitously as climate vulnerability receives greater emphasis. Under low climate vulnerability weighting, hydropower ranks second; under the baseline Very High weighting reflecting documented drought risks [2], [4], [6], hydropower drops to last place. Wind remains first across all scenarios, demonstrating robustness.

b. Grid Constraint Weight Variation

Table 12: The grid constraint weight variation

Grid Constraint Weight	Hybrid Rank	Solar Rank
Low (0.25)	4	3
Medium (0.50)	3	4
High (0.75)	3	4
Very High (1.00)	2	5

As grid constraint weight increases, hybrid systems (with battery storage) improve in ranking, moving from fourth to second under Very High weighting. The solar PV declines under high grid constraints due to curtailment without storage [3] (Table 12). This finding supports policies promoting hybrid renewable-battery configurations for grid-constrained areas [7].

5.3 Scenario Analysis

Optimistic Scenario (High weights on Technical and Economic, Low on Risk): Wind ranks first, hydropower second, geothermal third reflecting traditional least-cost planning [6]. Pessimistic Scenario (High weights on Risk, including Climate Vulnerability and Grid Constraints): Wind first, hybrid second, geothermal third, hydropower fifth the diversification imperative emerges clearly [3], [6].

Climate Scenario (Maximum weight on Climate Vulnerability): Geothermal and wind tie for first, hybrid third, hydropower last emphasizing that drought-resilient technologies should be prioritized [2], [4], [6].

5.4 Discussion

a. Implications for Ethiopia's Energy Policy

The results carry significant implications for Ethiopia's energy planning, particularly given the government's 17,000 MW expansion target and universal electrification goals [1][8]. First, the low ranking of large hydropower under climate vulnerability weighting suggests that continued prioritization of mega-hydro projects may be maladaptive. While hydropower has historically provided low-cost, low-carbon electricity, climate-induced drought risks documented by Naranjo-Silva (2025) [2] and Mekonnen (2022) [5] threaten generation reliability. Tewodros Mekonnen (2022) concluded that a 30% increase in total installed capacity would be required to compensate for anticipated 50% reduction in hydro plant output due to drought [5]. Policy should therefore cap hydropower expansion and redirect investment toward drought-resilient alternatives.

Second, wind energy's robust performance across sensitivity analyses supports accelerated wind deployment. Current capacity of approximately 324 MW [3] represents only a fraction of estimated potential. However, Nefabas et al. (2023) caution that wind curtailment could reach 9.8% at 25% annual energy share without adequate transmission and operational adjustments [3]. Recommendations include: (a) reducing minimum hydropower generation constraints to provide flexibility for wind integration, (b) expanding transmission capacity in wind-rich regions, and (c) implementing advanced dispatch protocols [3].

Third, hybrid solar-wind-battery systems merit expanded deployment, particularly for off-grid and weak-grid regions serving the population targeted for off-grid access under NEP-2 [8]. The REMCE minigrid cluster approach [7] aligns with this finding. Tefera Mekonnen's (2022) techno-economic analysis confirms that hybrid configurations are viable across all climate regions of Ethiopia, with grid-tied PV already below utility tariffs [5].

Fourth, geothermal development should be accelerated despite higher upfront costs. The very low climate vulnerability of geothermal [2] provides critical diversification benefits. Projections suggesting geothermal could contribute 7% of supply by 2065 [6] appear achievable but require addressing currency risk and technical capacity barriers identified in barrier analyses [15].

The optimistic scenario ranking (hydropower first, geothermal last) illustrates a critical policy dilemma. While hydropower appears economically attractive under stable climate assumptions, Ethiopia's recent drought-induced blackouts demonstrate that such optimism is misplaced [19], [23]. Decision-makers should not revert to hydropower-first planning despite its high CC in this scenario. Instead, the baseline framework, which gave climate vulnerability very high weight remains more aligned with observed climate trends [20], [24]. Geothermal's low ranking here reflects only short-term costs, ignoring its long-term resilience value [21]. For sustainable energy planning, multi-scenario analysis is essential. We recommend that Ethiopian policymakers adopt a diversified portfolio with wind, geothermal, and hybrid systems, using the optimistic scenario only as a lower-bound reference for hydropower's potential contribution [22], [25].

The radar chart reveals why hydropower's historical dominance is untenable under climate-adaptive planning (Figure 2). It's extremely high climate vulnerability and water consumption coupled with land use impacts outweigh its low LCOE and high capacity factor [19], [20]. Wind and geothermal exhibit the most balanced profiles, making them resilient to both drought and grid constraints [21], [22]. Hybrid systems, while penalized on grid integration due to standalone configuration assumptions, show strong social acceptance, a critical factor for rural deployment [24]. Solar PV's high energy access score supports its role in off-grid electrification, but currency risk and intermittency require hybrid storage solutions [23]. For policymakers, diversifying toward wind, geothermal, and hybrid-battery systems is essential. The optimistic scenario (Figure 1) should not override these baseline findings, as Ethiopia's recent droughts validate high climate vulnerability weights [20], [25].

b. Comparison with Existing Literature

Our findings align with but extend beyond existing studies. The climate vulnerability of Ethiopian hydropower documented by [2], [4], [6] is confirmed and quantified within a multi-criteria framework that compares hydropower directly against alternatives. The grid integration challenges identified by [3], [7] are incorporated as explicit criteria, revealing how curtailment risks affect alternative rankings.

The fuzzy MCDM approach adopted here follows methodological precedents established by AlKassem et al. (2025) for CSP technology selection [9] and recent Gaussian fuzzy applications for renewable energy productivity [14]. The novelty lies in the specific operationalization of climate vulnerability and grid constraints as criteria with Ethiopia-calibrated weights and data.

c. Limitations and Future Research

Several limitations warrant acknowledgment. First, the fuzzy decision matrix relies on literature synthesis rather than primary expert elicitation across all stakeholder groups. Future research should conduct structured Delphi studies with EEP engineers, Ministry of Finance officials, Environmental Protection Authority representatives, and regional administrators.
Second, the framework assumes static criteria weights, whereas actual policy priorities evolve over time. Dynamic fuzzy MCDM approaches incorporating time-dependent weights would better capture Ethiopia's energy transition trajectory.

Third, spatial heterogeneity is not addressed. Climate vulnerability varies across Ethiopia's river basins [4], and grid constraint severity differs between urban, peri-urban, and rural areas [7]. GIS-integrated fuzzy MCDM could address this limitation.
Fourth, the analysis does not incorporate the transboundary water politics affecting Nile hydropower [2]. While mentioned in the decision matrix, explicit weighting of regional political factors may affect large hydropower feasibility beyond purely technical climate vulnerability.

V. Conclusion

This study developed a fuzzy TOPSIS framework for prioritizing renewable energy supply systems in Ethiopia, with explicit incorporation of climate vulnerability and grid constraints as decision criteria. The framework evaluated five alternatives large hydropower, wind, solar PV, hybrid solar-wind-battery, and geothermal against fifteen sub-criteria across technical, economic, environmental, socio-political, and risk dimensions.

The results demonstrate that under climate-adaptive planning, wind and geothermal systems outrank conventional hydropower, which is severely penalized by drought vulnerability and grid constraints. Hybrid systems show strong performance for off-grid applications, supporting rural electrification priorities. Sensitivity analysis confirms that as climate vulnerability weighting increases, hydropower's rank declines precipitously from second under low weighting to last under very high weighting reflecting documented drought impacts.

For Ethiopian energy policy, these findings suggest that the historical prioritization of large hydropower should be reconsidered in favor of diversified portfolios emphasizing wind, geothermal, and hybrid renewable-battery systems. The framework offers a replicable decision-support tool for energy planners in hydropower-dependent developing economies facing analogous climate and infrastructure challenges.

Future research should validate the framework through primary expert elicitation, extend to dynamic weighting and spatial analysis, and incorporate transboundary water politics affecting Nile hydropower.

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