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Multi-Criteria Evaluation of Nuclear Energy (Small Modular Reactors) Scalability and Deployment Flexibility for Sustainable Electricity Supply in Northern Nigeria A TOPSIS-Based Approach

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Abstract: **Northern Nigeria faces acute electricity challenges due to weak grid infrastructure, transmission losses, water scarcity, and rising energy demand from population growth and industrialization. Renewable energy sources such as solar and wind, though abundant, are intermittent and insufficient to meet baseload requirements. In this context, Small Modular Reactors (SMRs) have emerged as a promising solution due to their modularity, safety features, scalability, and compatibility with hybrid energy systems. This study applied the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a multi-criteria decision-making (MCDM) method, to evaluate and rank four SMR technologies Light Water Reactor SMR (LWR-SMR), High Temperature Gas-Cooled Reactor SMR (HTGR-SMR), Molten Salt Reactor SMR (MSR-SMR), and Sodium-Cooled Fast Reactor SMR (SFR-SMR). Fourteen decision criteria were developed based on Nigeria's energy context, the results showed that LWR-SMR ranked highest (closeness coefficient = 0.5693), owing to its high technology readiness, proven commercial deployment, and financing maturity. HTGR-SMR ranked second (0.5575), excelling in water efficiency and renewable integration, which are vital in Northern Nigeria's arid climate. In contrast, SFR-SMR (0.4097) and MSR-SMR (0.3598) ranked lower due to technological immaturity, higher complexity, and limited financing pathways. The study concludes that LWR-SMR and HTGR-SMR are the most suitable options for first-phase deployment in Northern Nigeria, while advanced designs such as MSR and SFR may be considered in the long term as technology and regulatory capacity evolve.**

Keywords: **Energy Security, Intermittent, Insufficient, Northern Nigeria, Nuclear Power, Multi-Criteria Decision Making (MCDM), Small Modular Reactors (SMRs), TOPSIS.**

I. INTRODUCTION

Access to reliable and affordable electricity remains one of the most pressing challenges in Sub-Saharan Africa. Nigeria, the continent's most populous country, continues to face severe electricity shortages, with more than 80 million citizens lacking access to power [1]. The Northern region, in particular, is disproportionately affected due to weak grid infrastructure, limited renewable penetration, and socio-economic vulnerabilities [2]. These challenges hinder industrial development, education, healthcare delivery, and overall socio-economic growth.

To address the persistent energy deficit, Nigeria has prioritized diversification of its energy mix, with growing attention to nuclear power as part of its long-term strategy [2]. Nuclear energy is globally recognized for its ability to provide low-carbon, base-load electricity and contribute to climate change mitigation [3]. However, conventional large-scale nuclear reactors pose significant challenges in the Nigerian context, including high capital costs, extended construction times, extensive cooling water requirements, and the need for stable, large-scale grids [4].

Small Modular Reactors (SMRs) have emerged as a promising alternative. SMRs are advanced nuclear systems designed to be built in factories, transported to sites, and installed in modular configurations. Their key advantages include enhanced safety systems, smaller land footprints, lower upfront capital costs, and suitability for weaker or fragmented grids [1];[5]. Importantly, SMRs offer flexibility in deployment, making them particularly attractive for regions such as Northern Nigeria, where energy demand is growing but grid infrastructure remains fragile.

Despite increasing global interest in SMRs, limited research has assessed their suitability for deployment in Nigeria, particularly in the North. Existing studies have primarily focused on economic feasibility at the national level [6], with little attention to the socio-political, environmental, and regional constraints that shape energy planning in developing countries. Moreover, policy debates often neglect physics-based considerations such as water demand, fuel cycles, and load-following capabilities, all of which are critical in the Nigerian context [3]; [7].

This study addresses these gaps by applying a multi-criteria decision-making (MCDM) framework, specifically the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). TOPSIS allows for a structured ranking of SMR alternatives based on their closeness to an “ideal” solution, making it particularly suitable for complex decisions involving multiple dimensions [8]. By integrating technical, economic, environmental, and social factors, the study evaluates four SMR technologies: Light Water Reactor (LWR-SMR), High-Temperature Gas-cooled Reactor (HTGR-SMR), Molten Salt Reactor (MSR-SMR), and Sodium Fast Reactor (SFR-SMR) in the context of Northern Nigeria’s unique energy challenges.

The main objectives of this study are therefore to:

i. Identify and define key technical, economic, environmental, and social criteria relevant to SMR deployment in Northern Nigeria.

ii. Apply the TOPSIS method to evaluate and rank SMR technologies using expert judgment and secondary data sources.

iii. Provide policy-relevant recommendations on SMR adoption as part of Nigeria’s energy diversification strategy.

By combining physics-informed criteria with policy and socio-economic considerations, this research contributes to the growing literature on nuclear energy in developing countries. Furthermore, it provides a decision-making framework that policymakers and energy planners can adapt to similar contexts across Africa and other regions with comparable challenges.

II. METHODOLOGY

2.1 Research Design

This study employed a multi-criteria decision-making (MCDM) approach to evaluate the suitability of different Small Modular Reactor (SMR) technologies for deployment in Northern Nigeria. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was chosen as the evaluation framework because it enables alternatives to be ranked based on their relative closeness to an “ideal” solution [8]. TOPSIS has been widely applied in energy planning because it accommodates diverse technical, economic, environmental, and social factors [9]; [10].

Unlike purely economic models, this study integrates physics-informed dimensions such as water demand, thermal efficiency, neutron kinetics, and load-following behavior. This ensures that the evaluation reflects both Nigeria’s socio-political realities and the scientific principles underlying SMR operation [3].

2.2 Selection of Alternatives

The study selected four SMR technologies: LWR-SMR, HTGR-SMR, MSR-SMR, and SFR-SMR based on their global development status, cooling requirements, and suitability for weak or fragmented grids. These alternatives represent a balance of technology readiness, water use, fuel efficiency, siting flexibility, and waste management potential [3].

Four SMR technologies were selected as alternatives for evaluation, based on their maturity, global development status, and potential suitability for weak-grid regions:

i. Light Water Reactor (LWR-SMR): Most advanced in terms of deployment, with designs such as NuScale approved by regulators.

ii. High-Temperature Gas-cooled Reactor (HTGR-SMR): Offers high thermal efficiency and low water requirements, suitable for arid regions.

iii. Molten Salt Reactor (MSR-SMR): Provides advanced fuel cycle flexibility and inherent safety, though still at low technology readiness levels.

iv. Sodium-cooled Fast Reactor (SFR-SMR): Promises long-term sustainability and waste minimization, but faces significant financing and maturity challenges.

These options were selected to reflect a balance of proven, emerging, and advanced SMR technologies relevant to Nigeria’s policy and infrastructure context [3]; [5].

2.3 Selection of Evaluation Criteria

Criteria were identified from a review of global SMR deployment literature and Nigeria’s energy policy priorities (Energy Commission of Nigeria [2]; [4], resulting in 14 factors categorized into technical, economic, environmental, and social dimensions. Weighting was applied with higher emphasis on security, financing, grid compatibility, renewable integration, and water needs to reflect Northern Nigeria’s regional priorities [3]. These reflect the specific constraints of Northern Nigeria, such as fragile grids, limited water availability, and financing barriers [7]

2.4 Data Sources

The study employed both primary and secondary data sources.

i. Primary sources: Expert scoring derived from Nigeria’s *Revised National Energy Policy*, reports from the Energy Commission of Nigeria, and SMR project feasibility documents. Experts provided context-specific evaluations on security, financing, and socio-political considerations.

ii. Secondary sources: Peer-reviewed journal articles, IAEA/DOE/PNNL technical reports, World Economic Forum briefs, and vendor specifications [3]; [11]; [12].

The integration of expert judgment with scientific and policy documents ensured that the criteria weighting was both contextually relevant and physics informed.

2.5 TOPSIS Computation Steps

The TOPSIS method followed six structured steps:

Step 1. Construction of the Decision Matrix

The decision matrix $D = [x_{ij}]$ was constructed, where each element x_{ij} represents the performance score of alternatives i under criterion j, m: number of alternatives (here, 4 SMRs), n: number of criteria (here, 14) and x_{ij}: performance score of alternatives i under criterion j. Each SMR was evaluated against 14 criteria using a 1–9 scale. For example, water demand was assessed using reactor thermodynamic principles, with heat removal modeled via Newton’s Law of Cooling [13].

$$Q = hA(T_{core} - T_{coolant}) \qquad (1)$$

where Q is the heat transfer rate, h the heat transfer coefficient, A the heat exchange area, and $T_{core} - T_{coolant}$ the temperature difference driving cooling.

Thus, the decision matrix D is structured with SMRs as rows and evaluation criteria as columns, forming the foundation for subsequent normalization and ranking steps.

Step 2. Normalization of the Decision Matrix: Values were normalized to ensure comparability across criteria using the vector normalization approach.

Using the formula:

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

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

Step 3. Application of Weights: Each normalized value was multiplied by its assigned criterion weight to reflect its relative importance, calculated Using:

$$v_{ij} = w_j \times r_{ij} \qquad (3)$$

where w_j is the weight of criterion j, v_{ij}: weighted normalized value, w_j: weight assigned to criterion j and r_{ij}: normalized value. Weights were assigned based on regional priorities such as security, financing, and water scarcity.

Step 4: Identification of Ideal Solutions:

The Positive Ideal Solution (PIS) represents the best performance values, while the Negative Ideal Solution (NIS) represents the worst.

For benefit criteria:

$$v_j^+ = \max(v_{ij}), v_j^- = \min(v_{ij}) \qquad (4)$$

For cost criteria:

$$v_j^+ = \min(v_{ij}), v_j^- = \max(v_{ij}) \qquad (5)$$

where: v_j^+: positive ideal solution (best value) and v_j^-: negative ideal solution (worst value).

Step 5: Calculation of Separation Measures

Euclidean distances were calculated for each alternative relative to PIS and NIS.

To best

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \qquad (6)$$

To worse

$$D_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \qquad (7)$$

where: D_i^+: separation distance of alternative iii from the ideal best and D_i^-: separation distance of alternative iii from the ideal worst.

Step 6: Computation of Closeness Coefficient

Each alternative’s closeness to the ideal solution was computed.

$$C_i^* = \frac{D_i^-}{D_i^+ + D_i^-} \qquad (8)$$

where $0 \leq C_i^* \leq 1$.

C_i^* closeness coefficient of alternative i, D_i^-: distance to negative ideal solution and D_i^+: distance to positive ideal solution.

A higher C_i^* indicates a closer proximity to the ideal solution and thus higher suitability.

Step 7: Rank Alternatives

SMRs where ranked in descending order of C_i^*.

2.6 Analytical Tools

The analysis was conducted using Python (NumPy, Pandas) for data processing and numerical computation. Microsoft Excel was used for verification and result visualization. Output included decision matrices, weighted normalized matrices, and final TOPSIS scores, presented in both tabular and graphical formats.

III. RESULTS AND DISCUSSION

3.1 Results of TOPSIS Analysis

The evaluation process followed the structured steps of TOPSIS.

Table I: Raw Decision Matrix of SMR Alternatives (Scores on 1–9 scale)

Criterion	Type	Weight	LWR-SMR	HTGR-SMR	MSR-SMR	SFR-SMR
Security	Benefit	0.15	7	6	6	6
Financing	Benefit	0.14	8	6	5	5
Grid fit	Benefit	0.12	8	7	6	6
Flexibility	Benefit	0.10	6	8	7	7
Low water requirement	Benefit	0.09	4	9	8	9
Transportability	Benefit	0.07	7	7	6	6
Natural hazard safety	Benefit	0.06	7	8	7	8
Construction time	Cost	0.06	7	6	6	5
Fuel & waste handling	Benefit	0.05	6	6	7	8
Human resources	Cost	0.05	7	6	5	5
Public acceptance	Benefit	0.04	6	6	5	5
Technology readiness	Benefit	0.03	9	7	5	5
Land availability	Benefit	0.02	8	8	8	8
Build complexity	Cost	0.02	7	6	5	5

Table I: Presents the initial decision matrix, which captures raw performance scores across 14 criteria. A close look at the entries shows that LWR-SMR consistently achieved higher scores in technology readiness and financing availability, while HTGR-SMR performed strongly in low water requirement and flexibility. Conversely, MSR-SMR and SFR-SMR had lower raw scores in readiness and public acceptance, reflecting their technological immaturity and weaker social trust. This confirms the foundational differences between mature and advanced SMR designs [3]

Table II: Normalized Decision Matrix

Criterion	LWR-SMR	HTGR-SMR	MSR-SMR	SFR-SMR
Security	0.5587	0.4789	0.4789	0.4789
Financing	0.6532	0.4899	0.4082	0.4082
Grid fit	0.5882	0.5147	0.4411	0.4411
Flexibility	0.4264	0.5685	0.4975	0.4975
Low water requirement	0.2571	0.5785	0.5143	0.5785
Transportability	0.5369	0.5369	0.4602	0.4602
Natural hazard safety	0.4656	0.5322	0.4656	0.5322
Construction time	0.5793	0.4966	0.4966	0.4138
Fuel & waste handling	0.4411	0.4411	0.5147	0.5882

Criterion	LWR-SMR	HTGR-SMR	MSR-SMR	SFR-SMR
Human resources	0.6025	0.5164	0.4303	0.4303
Public acceptance	0.5432	0.5432	0.4527	0.4527
Technology readiness	0.6708	0.5217	0.3727	0.3727
Land availability	0.5000	0.5000	0.5000	0.5000
Build complexity	0.6025	0.5164	0.4303	0.4303

Normalization (Table II) ensured comparability across criteria with varying scales. The normalized values show that HTGR-SMR benefitted significantly from high scores in water efficiency, reinforcing its suitability for Northern Nigeria's arid climate. Meanwhile, SFR-SMR's relative improvement in waste handling became more evident after normalization, reflecting its potential in advanced fuel cycles [11].

Table III: Weighted Normalized Decision Matrix

Criterion	LWR-SMR	HTGR-SMR	MSR-SMR	SFR-SMR
Security	0.0838	0.0718	0.0718	0.0718
Financing	0.0914	0.0686	0.0572	0.0572
Grid fit	0.0706	0.0618	0.0529	0.0529
Flexibility	0.0426	0.0569	0.0497	0.0497
Low water requirement	0.0231	0.0521	0.0463	0.0521
Transportability	0.0376	0.0376	0.0322	0.0322
Natural hazard safety	0.0279	0.0319	0.0279	0.0319
Construction time	0.0348	0.0298	0.0298	0.0248
Fuel & waste handling	0.0221	0.0221	0.0257	0.0294
Human resources	0.0301	0.0258	0.0215	0.0215
Public acceptance	0.0217	0.0217	0.0181	0.0181
Technology readiness	0.0201	0.0157	0.0112	0.0112
Land availability	0.0100	0.0100	0.0100	0.0100
Build complexity	0.0120	0.0103	0.0086	0.0086

When weights were applied (Table III), regional priorities became clearer. Security and financing carried high weights, which strengthened the position of LWR-SMR. In contrast, although MSR-SMR showed acceptable performance in flexibility and safety, the lower weights attached to these criteria meant its overall competitiveness declined. This weighted matrix reveals how Nigeria's socio-political and financial realities directly shape SMR rankings, rather than purely technical performance.

Table IV: Ideal Best and Worst Values

Criterion	Ideal Best	Ideal Worst
Security	0.0838	0.0718
Financing	0.0914	0.0572
Grid fit	0.0706	0.0529
Flexibility	0.0569	0.0426
Low water requirement	0.0521	0.0231
Transportability	0.0376	0.0322
Natural hazard safety	0.0319	0.0279

Criterion	Ideal Best	Ideal Worst
Construction time	0.0348	0.0248
Fuel & waste handling	0.0294	0.0221
Human resources	0.0301	0.0215
Public acceptance	0.0217	0.0181
Technology readiness	0.0201	0.0112
Land availability	0.0100	0.0100
Build complexity	0.0120	0.0086

Table IV, shows the Euclidean separation distances of each SMR from the positive and negative ideal solutions. LWR-SMR recorded the shortest distance to the positive ideal (0.3095) and the longest distance from the negative ideal (0.4091), indicating it is closest to the ideal solution. In contrast, MSR-SMR showed the largest distance from the positive ideal (0.4238), underscoring its unsuitability in the near term. These quantitative distances illustrate the degree of separation between deployment-ready and experimental SMR technologies [5].

Table V: Final TOPSIS Results

Alternative	D^+	D^-	Closeness Coefficient	Rank
LWR-SMR	0.0333	0.0440	0.5693	1
HTGR-SMR	0.0294	0.0370	0.5575	2
SFR-SMR	0.0446	0.0309	0.4097	3
MSR-SMR	0.0445	0.0250	0.3598	4

The final closeness coefficients (Table V) provide a clear ranking: LWR-SMR (0.5693), HTGR-SMR (0.5575), SFR-SMR (0.4097), and MSR-SMR (0.3598). This confirms LWR-SMR as the most suitable option for Northern Nigeria, followed closely by HTGR-SMR. The narrow margin between LWR and HTGR suggests both designs are competitive, though HTGR's water efficiency gives it an edge for arid states [14].

Fig 1: Visual Hierarchy of SMR

Fig 1. visually reinforces the rankings from Table V. LWR-SMR and HTGR-SMR stand out as high-performing technologies, while SFR-SMR and MSR-SMR lag significantly behind. This bar chart provides policymakers with a **clear visual hierarchy** that supports evidence-based technology prioritization.

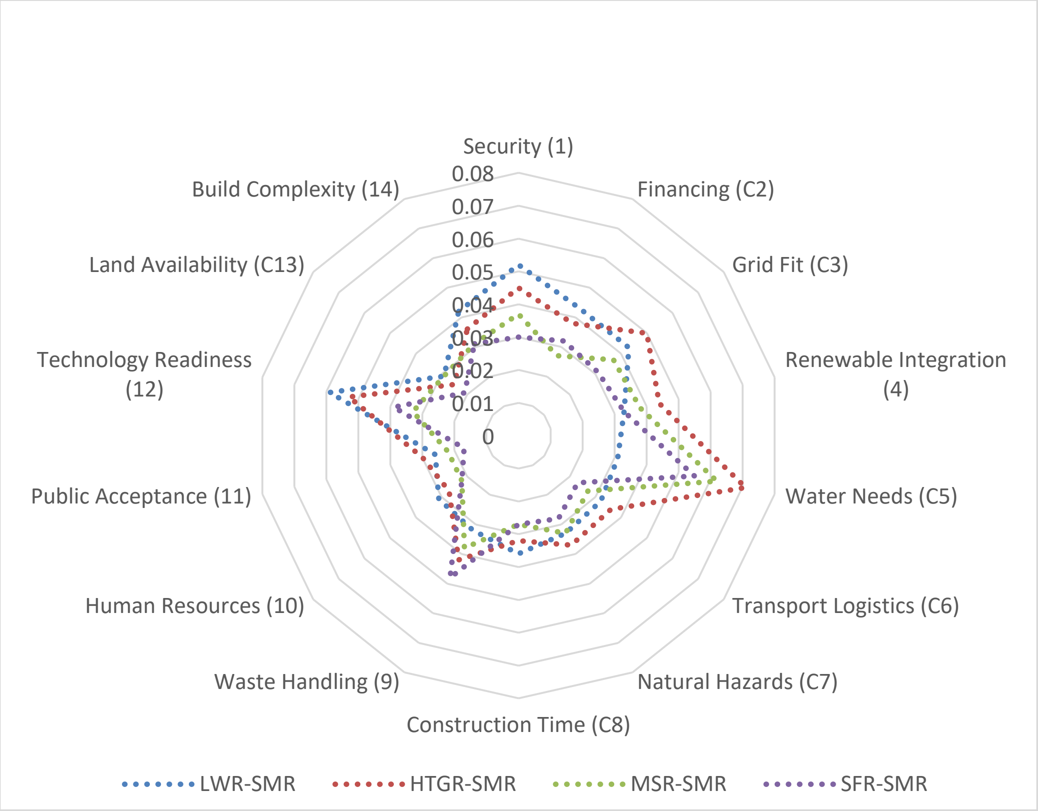

Fig 2: Radar chart of SMR performance across criteria

The radar chart (Fig 2) illustrates the comparative strengths of each SMR across all 14 criteria. HTGR-SMR dominates in **low water demand** and **flexibility**, making it highly attractive in Nigeria's dry Northern states. LWR-SMR demonstrates strong performance in **financing** and **readiness**, reflecting its maturity and global vendor support. SFR-SMR is strongest in **waste handling**, but this strength alone is insufficient to offset weaknesses in readiness. MSR-SMR appears relatively balanced but weak overall, with no standout advantages in Nigeria's context.

Overall discussion the results from Tables I – V and Figures 1 – 2 collectively show that SMR deployment in Northern Nigeria should begin with **LWR-SMRs** for their maturity and financing readiness, complemented by **HTGR-SMRs** for water-scarce contexts. Advanced designs such as SFR-SMR and MSR-SMR remain aspirational but are not yet feasible. These findings provide a balanced perspective that combines immediate energy needs with long-term sustainability goals, offering both academic contribution and practical policy guidance.

IV. CONCLUSION

In conclusion, while renewable energy remains central to Nigeria's energy transition, SMRs particularly LWR and HTGR offer a complementary and reliable pathway toward energy security, diversification, and climate goals. Early adoption could position Nigeria as a pioneer of SMR deployment in Africa.

This study contributes to knowledge by (i) demonstrating TOPSIS application for nuclear technology selection in developing contexts, (ii) integrating physics-based criteria into multi-dimensional assessments, and (iii) providing a region-specific roadmap for SMR deployment in Sub-Saharan Africa.

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