A Robust Framework for Small Modular Reactor Technology Selection: Application to Nigeria

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1. Introduction

Nigeria's electricity sector continues to face chronic under-capacity, with an effective grid output of only 4,000~5,300 MW compared with an installed capacity of approximately 13,000 MW. Frequent power outages and continued dependence on gas- and diesel-fired generation have intensified the need for reliable low-carbon baseload electricity. In response, Nigeria's Energy Transition Plan (ETP) targets net-zero emissions by 2060 and identifies nuclear power as a strategic long-term energy option [1]. Reflecting this policy direction, the Nigerian Minister of Power formally endorsed the deployment of Small Modular Reactors (SMRs) in 2025, citing their compatibility with weak power grids, reduced financing requirements, and shorter construction schedules [2].

Under the IAEA Milestones Approach, Nigeria is currently recognized as a Phase 2 nuclear newcomer country. Among the available nuclear technologies, SMRs offer several advantages for newcomer countries, including passive safety features, modular factory fabrication, and flexible deployment. However, selecting the most suitable SMR technology remains a complex multi-criteria decision problem requiring simultaneous consideration of technical performance, economics, safety, regulatory readiness, grid compatibility, and national infrastructure. Although several reactor assessment methodologies, including the IAEA Reactor Technology Assessment (RTA) and the KIND-ET Multi-Attribute Value Theory (MAVT) framework, have been developed to support technology selection, existing evaluations rely primarily on deterministic weighting assumptions and therefore provide limited insight into the robustness of technology rankings under stakeholder uncertainty [3].

To address this limitation, this study proposes a novel three-layer decision framework integrating (1) IAEA RTA qualitative screening, (2) KIND-ET deterministic multi-criteria evaluation, and (3) Monte Carlo-based stochastic robustness analysis. Unlike previous KIND-ET applications, the proposed framework systematically evaluates ranking stability by sampling stakeholder preference weights across 1,000, 5,000, and 10,000 independent Monte Carlo trials. This probabilistic extension enables the robustness of deterministic rankings to be quantified under realistic decision uncertainty and provides a more transparent and defensible basis for SMR technology selection. The proposed framework provides a general decision-support methodology for robust SMR technology selection under uncertainty and is readily transferable to other emerging nuclear energy countries beyond the Nigerian case.

2. Methods and Results

2.1 Reactor Technology Assessment

The Reactor Technology Assessment (RTA) methodology is a qualitative screening tool designed to compare candidate reactor technologies across ten Key Elements (KEs): site and environment, fuel cycle, nuclear safety, nuclear island design and performance, balance-of-plant (BOP) design and grid integration, BOP design for non-electric applications, safeguards and physical protection, technology readiness, project delivery, and economics and financing [4].

To reflect Nigeria's national priorities, customized weighting factors were assigned to the ten KEs as follows: nuclear safety (18%), site and environment (12%), nuclear island design and performance (12%), BOP design and grid integration (11%), safeguards and physical protection (10%), economics and financing (10%), project delivery (8%), non-electric BOP applications (7%), fuel cycle (6%), and technology readiness (6%). The weighting scheme was established through a systematic review of the Nigeria ETP, the NNRA Strategic Plan, and operational data published by the Nigerian Electricity Regulatory Commission (NERC). The proposed weights were subsequently validated through structured consultations with 11 Nigerian nuclear experts representing the Nigeria Atomic Energy Commission (NAEC), the Nigerian Nuclear Regulatory Authority (NNRA), the Centre for Energy Research and Training at Ahmadu Bello University, Zaria (CERT Zaria), and NERC.

Each candidate SMR technology was evaluated using a five-point scoring scale based on technical information obtained from the IAEA Advanced Reactor Information System (ARIS), vendor documentation, and expert survey responses. The weighted scores for all ten KEs were aggregated to obtain an overall qualitative assessment score for each candidate technology.

2.2 KIND-ET Methodology

The KIND-ET methodology is a quantitative evaluation method based on Multi-Attribute Value

Theory (MAVT) [5]. The methodology employs a hierarchical objectives tree structured into three levels: High-Level Objectives (HLOs), evaluation areas, and Key Performance Indicators (KPIs). Three HLOs were defined and weighted to reflect Nigeria's national priorities: Security and Sustainability (0.30), Safety and Environment (0.35), and Economics and Deployment (0.35). Eleven KPIs (FUEL, GRID, SAFE, RISK, WSTE, CAPX, LCOE, FIN, TRL, LOCL, and TIME) were evaluated for all eight candidate SMR technologies.

Raw performance scores on a five-point scale (3–5) were assigned based on data obtained from the IAEA ARIS, vendor documentation, and evaluations provided by the same panel of 11 Nigerian experts who validated the RTA weighting factors. The expert panel, comprising professionals from NAEC, NNRA, CERT Zaria, and NERC, confirmed that the relative performance rankings implied by the assigned scores were consistent with their expert judgement of each technology under Nigerian conditions. The scores were linearly normalized (score 3, V = 0.0; score 5, V = 1.0) and aggregated through weighted summation: $Si = \Sigma_j [w_j \times \Sigma\, k\, (w_{kj} \times V_{ij})]$, where w_j is the weight assigned to the *j*-th HLO and w_{kj} is the weight assigned to the *k*-th indicator within HLO_j.

2.3 Monte Carlo Stochastic Simulation

A Monte Carlo extension was implemented as a macro-enabled module within the KIND-ET Excel environment. In each simulation trial, the weights assigned to the three HLOs and the eleven indicator weights were independently sampled from triangular probability distributions defined by minimum, most likely (base-case), and maximum values. These distributions were calibrated to represent the realistic range of stakeholder priorities in Nigeria, while ensuring that the HLO weights summed to 1.00 in every trial. Performance scores were held constant throughout the simulations.

Three independent simulation runs comprising 1,000, 5,000, and 10,000 trials were performed using different random seeds. In each trial, the technology with the highest overall score was recorded as the rank-1 candidate. Simulation convergence was evaluated using $SE = \sqrt{p(1-p)/n}$, where p denotes the rank-1 winning probability and n represents the total number of simulation trials [6].

2.4 Evaluation Results

Eight SMR technologies were evaluated: ACP100 (125 MWe, CNNC), SMART100 (100 MWe, KAERI), NuScale VOYGR (77 MWe, NuScale Power), BWRX-300 (300 MWe, GE-Hitachi), i-SMR (170 MWe, KHNP-KAERI), AP300 (300 MWe, Westinghouse), RITM-200 (170 MWe, Rosatom), and NUWARD (170 MWe, EDF). Technical, safety, economic, and deployment data were compiled from IAEA ARIS [7] and NEA SMR Dashboard [8].

The qualitative RTA results are summarized in Table I. ACP100 achieved the highest overall RTA score (4.86), owing to its advanced deployment maturity, strong safety performance, and compatibility with Nigeria's grid characteristics and economic conditions. SMART100 ranked second (4.54), reflecting its strong potential for multi-purpose applications and excellent compatibility with a 100 MWe grid environment. NuScale VOYGR ranked third (4.50), supported by its U.S. NRC Standard Design Certification obtained in 2023. BWRX-300 and i-SMR ranked fourth (4.42) and fifth (4.38), respectively. NUWARD received the lowest score (3.62), primarily reflecting its relatively early stage of technology development.

Table I: RTA Qualitative Screening Results

SMR	Total Score	Company
i-SMR	4.38	KHNP
SMART100	4.54	KAERI
AP300	4.15	Westinghouse
RITM-200	4.08	Rosatom
NUWARD	3.62	EDF
BWRX-300	4.42	GE-Hitachi
ACP100	4.86	CNNC
NuScale	4.50	NuScale Power

The deterministic KIND-ET evaluation produced overall normalized scores on a 0~1 scale, as summarized in Table II together with the corresponding HLO-level contributions. ACP100 achieved the highest overall score (0.5942), primarily due to its superior performance in the Economics and Deployment objective (HLO3 = 0.2692), supported by maximum scores for LCOE, Project Financing, and Technology Readiness. SMART100 ranked second (0.5757), achieving the highest score in Security and Sustainability (HLO1 = 0.2250), reflecting its favorable unit capacity and grid compatibility. NuScale VOYGR ranked third (0.5714) and recorded the highest Safety and Environment score (HLO2 = 0.3500), representing the theoretical maximum for this objective through maximum scores in SAFE, RISK, and WSTE. A clear performance discontinuity separates the top five technologies from the remaining three, with a score difference of 0.376 between fifth-ranked i-SMR (0.5169) and sixth-ranked AP300 (0.1411), representing the largest gap between adjacent rankings.

Table II: KIND-ET Overall and HLO-Level Scores

SMR	Overall	HLO1	HLO2	HLO3
ACP100	0.5942	0.1500	0.1750	0.2692
SMART100	0.5757	0.2250	0.1750	0.1757
NuScale	0.5714	0.1500	0.3500	0.0714
BWRX-300	0.5592	0.1500	0.1750	0.2342

i-SMR	0.5169	0.2250	0.1750	0.1169
AP300	0.1411	0.0000	0.1173	0.0238
RITM-200	0.1404	0.0000	0.1173	0.0231
NUWARD	0.0000	0.0000	0.0000	0.0000

Fig. 1 illustrates the HLO-level score distributions obtained from the deterministic KIND-ET evaluation and the corresponding Monte Carlo rank-1 winning frequencies. Figure 1(a) compares the contributions of the three HLOs for all candidate technologies, while Fig. 1(b) presents the rank-1 winning frequencies obtained from the 1,000-, 5,000-, and 10,000-trial simulations. The Monte Carlo simulation results are summarized in Table III. Only three technologies of NuScale VOYGR, ACP100, and SMART100 achieved rank-1 status across the combined total of 16,000 simulation trials. The remaining five technologies recorded no rank-1 wins under any simulation scenario, indicating that none of the sampled stakeholder weighting combinations enabled a Tier-2 technology to outperform all three Tier-1 candidates simultaneously. This clear two-tier performance structure was consistently observed across all three simulation sizes.

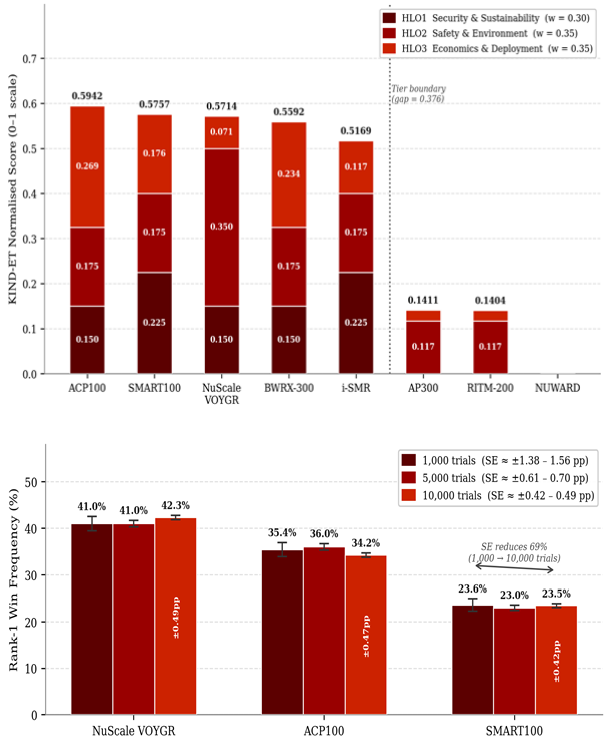


Fig. 1. KIND-ET HLO-level scores (a) and Monte Carlo rank-1 win frequencies (b).

Table III: Monte Carlo Rank-1 Win Frequencies

SMR	1,000 Trials	5,000 Trials	10,000 Trials	Dominant HLO Pillar
NuScale VOYGR	41.0%	41.0%	42.3%	Safety & Environment (HLO2)
ACP100	35.4%	36.0%	34.2%	Economics & Deployment (HLO3)
SMART100	23.6%	23.0%	23.5%	Security & Sustainability (HLO1)

NuScale VOYGR achieved the highest rank-1 winning frequency at all simulation scales, reaching 42.3% in the 10,000-trial analysis despite ranking third in both deterministic evaluation frameworks. Its superior stochastic performance reflects scenarios in which Safety and Environment receive the greatest stakeholder priority. ACP100 converged to a rank-1 winning frequency of 34.2%, performing most favorably when Economics and Deployment were assigned greater importance. SMART100 converged to 23.5%, dominating scenarios emphasizing Security and Sustainability. This three-way distribution corresponds directly to the three HLOs, demonstrating the internal consistency of the proposed evaluation framework. The standard error decreased from approximately ±1.56 percentage points at 1,000 trials to ±0.49 percentage points at 10,000 trials, representing a 68% reduction consistent with the law of large numbers.

Across both the qualitative RTA screening and the quantitative KIND-ET evaluation, ACP100, SMART100, and NuScale VOYGR consistently emerged as the three leading SMR candidates for Nigeria. The Monte Carlo analysis further confirmed this result by demonstrating that these three technologies collectively accounted for 100% of all rank-1 outcomes across the 16,000 simulation trials. Together, the deterministic and stochastic analyses provide complementary decision-support perspectives: ACP100 represents the preferred technology under Nigeria's current priority weighting, whereas NuScale VOYGR demonstrates the greatest robustness across a broad range of plausible stakeholder preference scenarios.

3. Conclusions

This study presents the first three-layer integrated framework for SMR technology assessment in Nigeria, combining qualitative screening using the IAEA RTA, quantitative evaluation through the KIND-ET methodology, and a novel Monte Carlo-based stochastic analysis comprising 16,000 independent weight simulations. The results consistently identify ACP100, SMART100, and NuScale VOYGR as the three leading SMR candidates. ACP100 achieved the highest rankings in both deterministic evaluations (RTA 4.86, KIND-ET 0.5942), primarily owing to its superior performance in the Economics and Deployment objective. In contrast, NuScale VOYGR demonstrated the greatest robustness under uncertainty, achieving the highest rank-1 winning frequency (42.3% in the 10,000-trial simulation) through its outstanding performance in

Safety and Environment. SMART100 ranked second in both deterministic evaluations and performed most favorably under scenarios emphasizing Security and Sustainability, with a rank-1 winning frequency of 23.5%. The remaining five technologies recorded no rank-1 wins across all 16,000 simulation trials, confirming a clear and robust two-tier technology classification.

The strong agreement between the RTA and KIND-ET rankings, together with the Monte Carlo simulation results, provides a transparent and defensible basis for SMR technology selection under uncertainty. The findings suggest that parallel engagement with CNNC, KAERI/KHNP, and NuScale Power represents an appropriate strategy during the early stages of vendor evaluation, prior to final technology selection. Although BWRX-300 ranked below ACP100 by only 0.035 points in the KIND-ET evaluation, its larger unit capacity makes it a more suitable option for future deployment as Nigeria's grid expands beyond approximately 7,000 MW.

Future research should extend the proposed framework by incorporating uncertainty in both performance scores and weighting factors, rather than weighting factors alone. In addition, integrating site-specific characteristics for candidate locations such as Geregu and Itu would further enhance the applicability and realism of the proposed decision-support framework. Although demonstrated through a Nigerian case study, the proposed framework is readily applicable to other emerging nuclear energy countries considering future SMR deployment.

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