Multi-Criteria Evaluation of Small Modular Reactors for Nuclear Newcomer Countries: A Case Study of Nigeria Using Integrated IAEA-Based Assessment Tools

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1. Introduction

Nigeria's energy sector is characterized by persistent under-capacity, with an effective grid power of approximately 5~6 GW, frequent power outages, and a heavy dependence on gas and diesel generation. These structural challenges have resulted in increased greenhouse-gas emissions, elevated electricity costs, and constraints on economic growth. In response, Nigeria's Energy Transition Plan (ETP) sets a national target of achieving net-zero emissions by 2060, emphasizing the expansion of renewable energy, improvements in energy efficiency, and the introduction of nuclear power to provide reliable baseload electricity. Within the framework of the IAEA milestones approach, Nigeria is classified as a phase-2 nuclear newcomer country. In this context, small modular reactors (SMRs) have been identified as a promising nuclear technology due to their modular construction, enhanced safety characteristics, lower upfront capital requirements, and compatibility with fragmented and capacity-constrained electricity grids. SMRs, typically defined as reactors with unit capacities below 300 MWe, incorporate passive safety systems, factory-based fabrication, and flexible deployment strategies that allow phased capacity additions aligned with national infrastructure development. Nigeria's nuclear institutions, including the Nigeria Atomic Energy Commission (NAEC) and the Nigerian Nuclear Regulatory Authority (NNRA), are actively engaging with the IAEA to advance SMR planning activities [1]. These efforts include international technical cooperation, participation in SMR-focused conferences, and capacity-building initiatives supported by international partners. Despite this progress, a key challenge remains the objective selection of SMR technologies that best align with Nigeria's technical, economic, regulatory, and infrastructural conditions.

This study addresses this challenge by applying an integrated assessment framework based on IAEA methodologies. The objectives of the study are to: (1) evaluate candidate SMR technologies using the reactor technology assessment (RTA) and the key indicators for innovative nuclear energy systems evaluation tool (KIND-ET); (2) adapt these assessment frameworks to reflect Nigeria's national priorities and constraints; and (3) identify robust SMR options that support sustainable and reliable nuclear power deployment in Nigeria. Compared with prior IAEA-aligned studies that predominantly employ RTA or KIND-ET as standalone tools and examine a limited set of SMR options [2,3,4], this study proposes a sequential hybrid assessment framework that systematically integrates qualitative expert-based RTA screening with quantitative KIND-ET multi-attribute value analysis across eight SMR designs under Nigeria-specific boundary conditions. This integrated and expanded approach enhances methodological robustness by mitigating expert subjectivity and weighting bias, while providing a more comprehensive and transferable basis for technology prioritization in nuclear newcomer countries with constrained grids and resources.

2. Methods and Results

2.1 Reactor Technology Assessment

The Reactor Technology Assessment (RTA) is a qualitative screening methodology designed to compare reactor technologies across a comprehensive set of evaluation criteria [5]. The RTA framework consists of 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, economics and financing. To reflect Nigeria's specific priorities as a nuclear newcomer country, customized weighting factors were applied to 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 (7%), fuel cycle (6%), and technology readiness (6%). Each reactor technology was scored on a five-point scale based on data obtained from the IAEA advanced reactor information system (ARIS), publicly available vendor documentation, and Nigerian experts' survey results. The weighted scores were aggregated to obtain an overall qualitative ranking for each SMR technology.

2.2 KIND-ET Methodology

The KIND-ET tool is a quantitative evaluation methodology based on Multi-Attribute Value Theory (MAVT) [6]. The approach employs a hierarchical objectives tree structured across three levels: high-level objectives (HLOs), evaluation areas, and key performance indicators. For this study, three HLOs were defined and weighted to reflect Nigeria's national context: security and sustainability (0.30), safety and environment (0.35), and economics and deployment (0.35). Relative weights at each level of the hierarchy were assigned by subject-matter experts using a normalized scale from 0 to 1, with weights summing to unity at each branch. Raw performance data for each indicator such as fuel characteristics, grid compatibility, and levelized cost of electricity (LCOE) were transformed into single-attribute value functions using linear normalization. The overall score for each reactor technology was calculated through weighted aggregation of the normalized indicator values. Sensitivity analyses were performed by varying key weights by ±10% to verify the robustness of the resulting rankings.

2.3 Evaluation Results

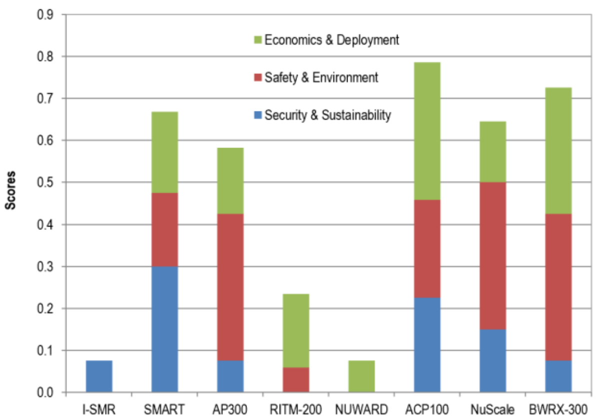
Eight SMR technologies representing diverse design philosophies, vendors, and deployment strategies were selected for evaluation. They are: i-SMR (170 MWe), SMART100 (100 MWe), AP300 (300 MWe), RITM-200 (55 MWe), NUWARD (170 MWe), BWRX-300 (300 MWe), ACP100 (125 MWe), and VOYGR (77 MWe). Technical, safety, economic, and deployment data were compiled from IAEA databases, vendor publications, and recent project updates [7]. The RTA methodology was applied as an initial qualitative screening tool to assess broad compatibility with Nigeria's national priorities, while the KIND-ET tool provided quantitative refinement and ranking. The combined use of both methodologies enhances transparency, mitigates methodological bias, and strengthens the credibility of the final recommendations.

The RTA results reflect the performance of each SMR technology against Nigeria-specific weighted KEs, with particular emphasis on nuclear safety, project delivery feasibility, grid and BOP compatibility, passive safety features, and deployment readiness. ACP100 achieved the highest overall RTA score (4.86), driven by its advanced deployment maturity, strong safety characteristics, and compatibility with Nigeria's grid and economic conditions as shown in Table I. SMART100 demonstrated strong performance in multi-purpose applications and safety, while NuScale VOYGR benefited from regulatory maturity, including certification by the U.S. Nuclear Regulatory Commission. The KIND-ET evaluation produced overall normalized scores on a 0~1 scale. ACP100 ranked first with a score of 0.785, followed by BWRX-300 (0.725), SMART100 (0.668), and VOYGR (0.644) as shown in Fig. 1. Sensitivity analyses confirmed that the relative rankings remained stable under reasonable variations in weighting assumptions, indicating robustness of the results.

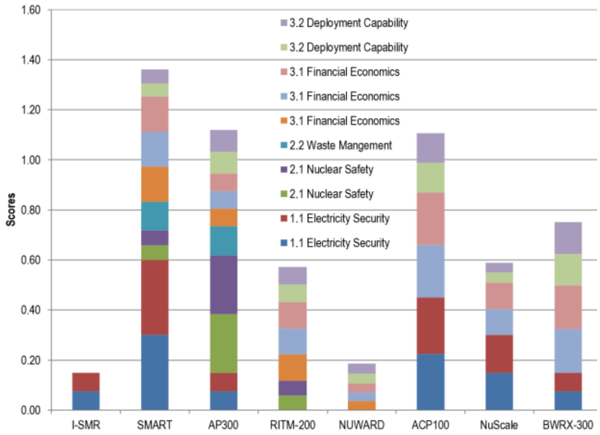
Across both the qualitative RTA screening and the quantitative KIND-ET evaluation, ACP100, SMART100, and VOYGR consistently emerged as the most suitable SMR options for Nigeria. This convergence reflects strong alignment with Nigeria's needs as a nuclear newcomer country, including limited grid capacity, the need for phased capacity expansion, financing constraints, regulatory capacity development, and a strong emphasis on passive safety and long-term sustainability. ACP100 ranked first in both methodologies due to its advanced deployment status, integral pressurized water reactor design with passive safety systems, moderate unit size, and favorable compatibility with Nigeria's technical and economic conditions. SMART100 and VOYGR also demonstrated robust performance, particularly in safety, environmental impact, and grid integration, supported by recent regulatory milestones and mature design features. Although BWRX-300 achieved a high score in the KIND-ET evaluation due to favorable economic indicators and near-term deployment prospects, its lower RTA ranking highlights the impact of larger unit size on deployment flexibility during the early stages of Nigeria's nuclear program. This outcome underscores the value of combining qualitative and quantitative assessment tools to achieve a balanced and transparent technology selection process.

Table I: RTA Results

SMR	Total Score	Company
i-SMR	4.33	KHNP
SMART100	4.54	KAERI
AP300	4.43	Westinghouse
RITM-200	4.22	Rosatom
NUWARD	4.23	EDF
BWRX-300	4.49	GE Hitachi
ACP100	4.86	CNNC
VOYGR	4.50	NuScale



(a)



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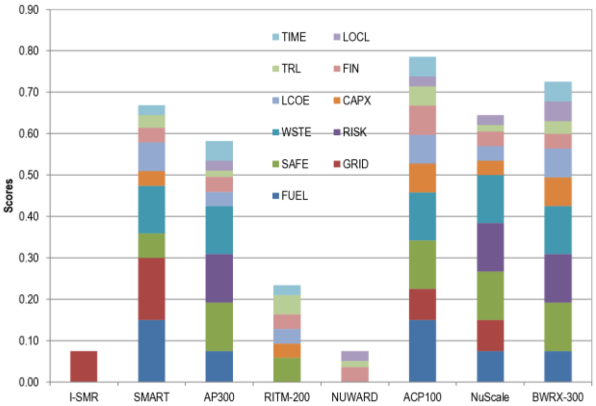

(c)

Fig. 1. Ranking result based on HLOs (a), evaluation areas (b) and final scores (c).

3. Conclusions

This study presents an integrated IAEA-based assessment of small modular reactor technologies for Nigeria's nuclear power programme, combining qualitative screening through the RTA and quantitative evaluation using the KIND-ET tool. The results consistently identify ACP100, SMART100, and VOYGR as the most suitable SMR options for Nigeria, aligning with national objectives for reliable, low-carbon electricity generation under grid and financial constraints. The convergence of results from both assessment methodologies provides a transparent and defensible foundation for informed decision-making and supports the strategic advancement of Nigeria's nuclear power program. Future work should focus on site-specific assessments, detailed economic modeling, and international partnerships to facilitate successful SMR deployment.

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