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Small Reactors, Big Questions: Rethinking Nuclear Regulation in Ghana for Small Modular Reactors

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ABSTRACT

The deployment of small modular reactors (SMRs) presents significant regulatory challenges for newcomer countries with evolving legal, technical and institutional frameworks. This study assesses Ghana's readiness to licence and regulate SMRs through benchmarking of its regulatory framework and institutional capacity against selected newcomer and mature nuclear regulatory bodies. The study finds that Ghana has established an important foundation for SMR regulation through its existing nuclear law, an operational regulatory authority and experience in research reactor oversight. However, regulatory readiness remains partial and evolving. The most significant gaps identified include the draft status of key regulations and licencing process documents, limited SMR-specific technical capacity and constrained financial sustainability. The study recommends prioritising the promulgation of core regulations, developing clear guidance for the implementation of graded approach for SMRs, conducting an SMR-specific regulatory competence self-assessment and institutionalising early stakeholder engagement and regulatory cooperation. Overall, Ghana has a credible basis for future SMR oversight, but targeted regulatory and institutional strengthening remains essential for effective SMR licencing and oversight.

1 | Introduction

Economic growth and social development, including health and education, are significantly influenced by access to electricity in both high- and low-income countries [1]. Developing economies, therefore, spend a greater proportion of their GDP on the importation of fossil fuels to maintain energy supply [2]. However, the heavy reliance on fossil fuels poses negative environmental consequences that hinder sustainable development. Climate change and its associated costs have emerged as a serious threat to Ghana's economic progress. According to the country's Fifth National Communication to the United Nations Framework Convention on Climate Change (UNFCCC) in 2022, the energy sector was the largest source of greenhouse gas emissions in 2019, accounting for 45.7% of total national emissions (59.8 MtCO₂e) [3]. This marked a

shift from 2018, when agriculture, forestry and other land uses (AFOLU) was the leading emitter. More recent national statistics show that in 2023, Ghana's total installed electricity capacity was dominated by thermal plants, which contributed 69.6%, compared to 28.1% from hydro and just 2.3% from other renewable sources. In terms of the broader energy supply, oil constituted 37.7%, natural gas 26.4%, biomass 29.8% and hydro 6%, while solar power made up less than 1% [4]. This profile illustrates a strong dependence on fossil fuels for both electricity and primary energy, with only a modest penetration of modern renewables. Hence, it has become imperative for Ghana to transition its electricity generation towards a low-carbon pathway. Nuclear power is increasingly being considered as a feasible and sustainable option to address this growing energy shortfall. Ghana's National Energy Transition Framework (2022–2070) outlines a future energy mix that

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incorporates hydropower, natural gas, renewables and nuclear power by 2030 [5]. While conventional large reactors offer a robust solution, Ghana is also exploring the potential of SMRs. In 2024, a landmark commercial agreement was signed between U.S. and Ghanaian nuclear firms to advance SMR project in Ghana [6]. Building on this momentum, Ghana has identified both the United States and China as key vendor partners for its first nuclear power plants, an important milestone in diversifying its future energy mix. While formal contracts are still pending, the direction is clear: U.S.-based NuScale Power, together with Regnum Technology Group and Japanese partners, has been positioned to advance SMR deployment, whereas China National Nuclear Corporation (CNNC) has been selected to develop a larger reactor [7]. This dual-track approach reflects Ghana's strategy of exploring both modular technologies and conventional large-scale designs, signalling a bold commitment to nuclear energy as part of its long-term development vision.

Despite these developments, most national studies have concentrated on the feasibility of conventional large nuclear power plants, with limited focus on the specific opportunities and challenges associated with SMR deployment in Ghana [8, 9]. This gap in analysis is significant, as SMRs' operational novelty present a unique regulatory consideration that differ from traditional reactors and shall be particularly relevant for nuclear newcomer countries. This study, therefore, examines Ghana's readiness to regulate SMRs by assessing the adequacy of its current legal and regulatory framework, identifying key legal, procedural, technical and institutional gaps, and analysing opportunities for strengthening preparedness. To situate Ghana's readiness in an international context, the study undertakes a comparative analysis across four key SMR regulatory readiness indicators: legal and licencing framework, human resource capacity, financial sustainability and stakeholder engagement. These indicators are used to benchmark the Nuclear Regulatory Authority (NRA) of Ghana against the Nuclear Regulatory Authority (NDK) of Turkey, the Federal Authority for Nuclear Regulation (FANR) of the UAE, the United States Nuclear Regulatory Commission (USNRC) and the Canadian Nuclear Safety Commission (CNSC). By drawing insights from both newcomer and established regulators, the study develops policy-relevant recommendations for improving SMR regulatory preparedness in Ghana and offers a useful reference point for other newcomer countries.

Ghana has demonstrated strong commitment to nuclear power through sustained institutional progress. Since officially launching its nuclear programme in 2007, the country has advanced under the IAEA Milestones Approach, completing Phase 1 by fulfilling all 19 infrastructure requirements for site development [10]. Recent initiatives such as the establishment of the E2 SMR Simulation Centre at the School of Nuclear and Allied Sciences (SNAS) [11] and Ghana's participation in the 2025 SMR School launch in Kenya [12] reflect a growing national and regional engagement with SMR technology. These developments highlight the need for the regulatory framework to evolve in readiness for the unique requirements of SMR deployment in Ghana.

The study begins by outlining Ghana's need for clean energy and its progress in nuclear power development before presenting an overview of SMRs, their types, development stages, benefits, drawbacks and global regulatory challenges. It then examines

key regulatory challenges, including licencing adaptation, technical human resource gaps, financial constraints and stakeholder engagement followed by strategic pathways aimed at strengthening Ghana's preparedness for safe and effective SMR deployment.

2 | Overview of Small Modular Reactors (SMRs)

2.1 | Current Global SMR Development Landscape and Design Features

SMRs are defined by several key characteristics: (1) a generation capacity of less than 300 MWe or under 1000 MWt per unit [13]; (2) a primary design intended for commercial power generation, distinguishing them from research and test reactors; and (3) the capability for multiple reactor modules to be co-located within a single facility using shared infrastructure [14]. The IAEA [15] defines SMR as advanced nuclear reactors with a power capacity of up to 300 MWe per unit approximately one-third the output of conventional nuclear power reactors. SMRs are distinguished from conventional nuclear power plants by their reduced size and core power, which lowers decay heat, enhances stability and limits radionuclide inventories. Many designs incorporate novel technologies such as passive safety systems, natural circulation cooling, integral reactor vessels and innovative fuel types, offering potential improvements in safety and performance [16]. Their modular nature enables factory-based fabrication and simplified construction, while also raising new considerations related to multi-module interactions, staffing and shared systems. Flexible deployment options including underground, floating or remote siting further expand their applicability, supported by the transportability of modules for construction, operation or refuelling [13].

The growing interest in SMRs can largely be attributed to their distinctive features particularly their compact size and modular construction as well as their versatility in a range of applications, including electricity generation, district heating, hydrogen production and seawater desalination [17]. As of 2024, more than 80 SMR designs and concepts have been identified worldwide, spanning six main technology categories: marine-based water-cooled SMRs (6 designs), fast neutron spectrum SMRs (10 designs), molten salt SMRs (12 designs), high-temperature gas-cooled SMRs (14 designs), micro-sized SMRs (14 designs) and land-based water-cooled SMRs (15 designs) according to the IAEA [18]. These designs are at different stages of maturity, ranging from conceptual design and basic design to detailed design, construction and operation (Figure 1) with some claimed as being near-term deployable. This diversity reflects both the global momentum behind SMR development and the search for flexible nuclear technologies suited to different national contexts. While the number of designs is continually evolving, the current landscape highlights the scale of innovation shaping the future of nuclear power.

The diversity and technological heterogeneity in SMR designs have significant implications for regulatory supervision, particularly for a newcomer country like Ghana. The wide spectrum of SMR technologies, ranging from water-cooled, metal cooled, molten salt systems and high-temperature gas-cooled concepts challenges the traditional assumption of design standardisation that has historically underpinned nuclear regulatory practice.

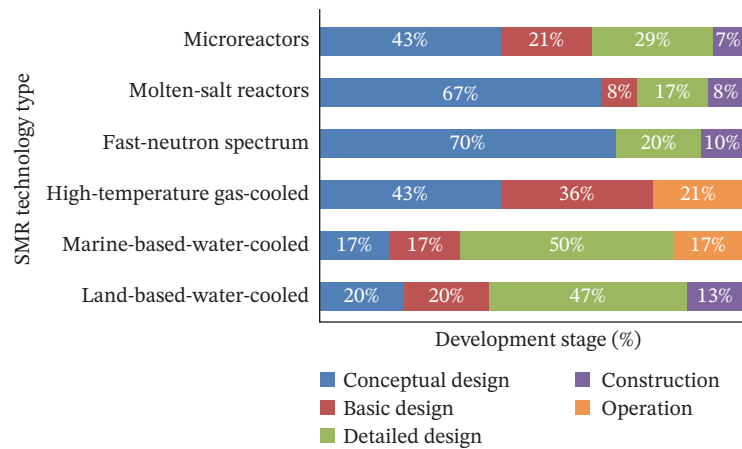


FIGURE 1 | Global distribution of SMR designs: technology types and development stages [18].

Regulatory bodies must be prepared to assess fundamentally different safety philosophies, fuel forms, coolant systems, neutron spectra and decay heat removal strategies [19]. This increases the technical breadth required within review teams and complicates the development of technology-neutral regulatory guidance. In the absence of harmonised international design standards, newcomer regulators may face increased number of requests for additional information (RAIs), extended review timelines and greater reliance on external expertise all resulting to extra financial burden on the regulator and the nuclear programme as a whole. The varying maturity levels of SMR designs introduces regulatory uncertainty as many designs remain at conceptual or basic design stages. This means that safety cases may be supported by limited operational data or unvalidated modelling assumptions. For first-of-a-kind (FOAK) deployments, regulators must evaluate safety analyses with reduced empirical evidence, increasing the depth and conservatism required in review. This may necessitate enhanced probabilistic safety assessment scrutiny, independent verification of modelling tools and more stringent quality assurance (QA) oversight.

2.2 | Potential Advantages and Challenges Associated With SMRs

SMR proponents have made a number of assertions about the potential advantages of the technology for both developed and developing nations, especially in the context of achieving social and environmental goals [20]. National agencies like the U.S. Department of Energy (USDoe) [21] and international nuclear energy advocacy groups like the IAEA [13] and the Nuclear Energy Agency (NEA) [22] have backed these claims amidst some potential challenges.

SMRs' compact footprint allow for easier transportation, installation, and integration into a wide range of locations, including remote or space-constrained areas [23]. The use of factory-fabricated components not only streamlines construction and reduces on-site assembly time but also improves quality control (QC). By requiring less land and infrastructure, SMRs can be deployed in regions where space is limited or in proximity to existing industrial facilities, offering flexibility that large conventional reactors cannot easily provide [24]. While the compact footprint and factory-based fabrication of SMRs offer deployment flexibility, they introduce complex regulatory challenges. Oversight must extend

beyond the plant site to include factory manufacturing, supply chain QA and transport of major nuclear components, potentially across national borders. This requires clear jurisdictional authority, harmonised certification standards and inspection access to foreign facilities [25]. Deployment in remote or industrial locations also complicates site evaluation, emergency preparedness (EP), security arrangements and infrastructure adequacy. Regulators must assess cumulative risks associated with co-location near existing facilities and ensure that reduced land requirements do not compromise exclusion zones, environmental protection, or defence-in-depth (DiD) principles.

Many SMR designs incorporate passive safety systems that rely on natural forces such as gravity, convection and heat dissipation, reducing dependence on active operator intervention or external power sources during emergencies. This intrinsic safety profile strengthens resilience against severe accidents while also demanding design adaptations to local conditions [26]. Another safety advantage stems from their low nuclear material inventory, low core power capacity and larger surface-to-volume ratio, which facilitate reduced residual heat, easier decay heat removal, broader site suitability and lower cooling requirements. Additionally, their inherently compact design can increase resistance to external hazards such as earthquakes and reduce vulnerability to intentional attacks [27]. Although passive safety systems in SMRs are intended to enhance safety by reducing reliance on active components and operator actions, they present distinct regulatory challenges. Their performance depends on relatively small driving forces such as gravity, natural circulation or pressure differentials, which may be sensitive to environmental conditions and parameter uncertainties, thereby requiring rigorous margin analysis to avoid cliff-edge effects. Failure modes may differ from those of active systems, with phenomena such as non-condensable gas accumulation or minor leakages potentially compromising functionality [28]. Regulators must also assess risks of inadvertent actuation, validate modelling assumptions for FOAK designs, and ensure adequate monitoring, maintenance and human oversight during accident conditions.

Equally important is the modular scalability of SMRs, which enables capacity to be expanded incrementally by adding reactor units in response to growing demand. This flexibility supports integration into both national grids and off-grid systems, making SMRs suitable for a variety of energy markets. The modular,

factory-based approach to manufacturing components enhances efficiency, reduces overall project costs and accelerates deployment compared to traditional large-scale nuclear plants [22, 29]. The varying interpretations and applications of modularity in SMR designs introduce substantial regulatory and safety management challenges. While some modules resemble prefabricated components used in large nuclear power plants such as modularised civil structures and traditional loop-based architectures [30], others integrate the entire nuclear steam supply system including the reactor core, containment and instrumentation and control into a single factory-fabricated unit [31]. This shifts significant construction, commissioning and QA activities from the plant site to manufacturing facilities, potentially located in different jurisdictions. Consequently, this complicates inspection authority, regulatory oversight and the legal classification of activities as either manufacturing or construction. Furthermore, modularity carries inherent safety implications for which the licensee must demonstrate sufficient competence to ensure nuclear safety. However, given the limited global experience with modular new builds, many developers and licensees lack practical familiarity with the safety implications of modular procurement, manufacturing, commissioning and operation. These implications include constrained inspection and maintenance access due to compact module layouts, integration challenges among safety-significant digital instrumentation and control systems, verification of electronic system compatibility, assurance of consistent factory quality standards and maintaining effective regulatory oversight across distributed production schedules [32]. The limited operational experience from completed SMR projects further increases uncertainty in safety demonstration and regulatory evaluation. Other aspects of SMR designs that influence security risk and may warrant rethinking security regimes include variations in insider and cyber threats linked to autonomous operation and remote monitoring, increased reliance on off-site response forces and the implications of compact designs where concentrated targets could compromise safety features if damaged simultaneously. Structural configurations, such as underground construction, can mitigate certain threats like aircraft impact but introduce others like flooding [33]. Remote or mobile installations pose challenges for timely external response, while supply chain vulnerabilities may heighten insider threat risks.

2.3 | Global SMR Regulatory Challenges

While SMRs hold significant promise for expanding nuclear power generation, their limited operational experience poses a unique challenge for regulators worldwide. Unlike large commercial reactors, which benefit from decades of accumulated safety cases and regulatory precedents, SMRs introduce novel designs, siting options and deployment models that fall outside existing regulatory frameworks. This creates a scarcity of practical regulatory experience, as authorities must evaluate safety, licencing and oversight processes without relying on well-established benchmarks.

2.3.1 | Legal and Regulatory Framework

A key global challenge in regulating SMRs lies in adapting existing legal and regulatory frameworks. Across countries, these

frameworks differ in approach—some being performance-based, others prescriptive—but most draw heavily on IAEA safety standards as reference points, particularly at the level of safety fundamentals [34, 35]. However, these safety standards, and the national frameworks they have inspired, were largely developed in the context of traditional large land based water cooled reactors [36]. With many states, including newcomer countries, now exploring SMRs that incorporate novel technologies, design concepts and deployment models, regulatory systems face the task of evolving beyond their original land based water cooled-centric foundations [16]. This challenge extends to nuclear security, where prescriptive regulations have historically dominated. The revision of these security regulations is increasingly necessary to account for how innovative SMR designs and approaches can offer both new vulnerabilities and new opportunities for strengthening protection against threats. While regulators in countries with technology-neutral, goal-setting regimes such as Argentina, Canada and the UK generally report no fundamental need for new regulations, they acknowledge the necessity for additional interpretative guidance to address innovative SMR features.

A case in point is NuScale Power's request for clarification on the term 'credible' in several sections of the NRC Regulations Title 10, Code of Federal Regulations (10 CFR). In the absence of a clear regulatory definition, the term was subject to differing interpretations among reviewers, introducing uncertainty into the review process. This lack of consistency can lead to unpredictable regulatory expectations, prolonged review timelines and increased licencing costs, including for events with extremely low frequencies and limited radiological significance [37]. A further illustration is provided by the joint early review of the NUWARD SMR. The review involved six European regulators (France, the Czech Republic, Finland, the Netherlands, Sweden and Poland) operating within broadly aligned Euratom, European Nuclear Safety Regulators Group (ENSREG) and Western European Nuclear Regulators' Association (WENRA) frameworks. Despite significant convergence at the level of laws and decrees, the review found that most divergences arose not from primary regulatory requirements but from differences in guidance and interpretation, as well as, in some cases, national non-nuclear legal provisions [38]. This highlights that SMR regulatory readiness depends not only on the existence of formal legal frameworks, but also on the early clarification of guidance, interpretative consistency and the identification of broader legal constraints that may affect design acceptability. For newcomer countries, such ambiguities pose heightened risks: without prior guidance, applicants may face delays, misinterpretations or inconsistent regulatory expectations, which can increase licencing time, cost and uncertainty.

Regarding regulatory requirements, Russia reported that while its existing regulations currently cover floating nuclear power plants (FNPPs), additional research is being undertaken to determine how best to adapt these requirements for land-based SMRs. In particular, the regulatory body is assessing whether existing rules can accommodate the case of serial production of modular reactors or whether entirely new regulatory provisions will be required [39]. The USNRC in the review of the NuScale safety analysis report, provided some exemptions and modified the existing regulations regarding the number of certified operators for a unit. The USNRC's existing staffing requirements under 10 CFR 50.54(k) and 50.54(m)(2)(i) and (iii) required a licenced

operator at the controls of every fuelled unit, rules built for traditional single or dual-unit reactors. NuScale however proposed that, six operators could manage 12 modules from one control room, which conflicted with 50.54(m)(2)(i) and (iii). The NRC accepted NuScale’s technical justification in the design certification application and embedded the new staffing requirements directly into the final requirement under Appendix G of 10 CFR Part 52, eliminating the need for future applicants to seek individual exemptions [40]. This illustrates that even where existing regulations remain broadly applicable, SMR deployment may still require targeted modifications to account for multi-module operating concepts and other non-traditional design features.

2.3.2 | Licencing Challenges

Authorisation is one of the most critical and resource-intensive aspects of deploying nuclear power plants, and the emergence of SMRs has introduced new complexities that strain traditional frameworks. Conventional licencing processes are structured around siting, design approval, construction, commissioning, operation, decommissioning and release from regulatory control [41]. However, SMRs require regulators to adapt these stages to account for factory fabrication, modular transportation, on-site and offsite assembly and in some cases, offsite decommissioning. This calls for additional regulatory hold points, certification steps and oversight mechanisms that are not yet fully established in most jurisdictions. While established regulators can at least adapt existing frameworks incrementally, newcomer regulators like Ghana must develop the authorisation framework from scratch. This creates a foundational risk where the newcomer country may either over-engineer its framework by defaulting to large reactor precedents, imposing strict restrictions that could negate SMR economics, or under-engineer it by failing to anticipate the cross-boundary oversight demands unique to modular deployment. Either outcome has serious implications for safety, cost and schedule.

The licencing of a FOAK SMR can be both lengthy and resource-intensive, with costs largely independent of power output. This diseconomy of scale disproportionately burdens SMRs, undermining their economic competitiveness compared to large reactors [42]. For instance, Vogel and Quinn [43] found that applying the same annual regulatory fee to a 45 MWe SMR and a 2000 MWe large reactor results in a licencing cost per kilowatt that is over 20 times higher for the SMR. For regulators, this raise concerns not only about fairness and credibility of the fee structures, but also about efficiency in ensuring safety without pricing SMRs out of the market. Ultimately, such high licencing costs may translate into higher electricity prices, with the public bearing the burden, making this a critical regulatory challenge

The USNRC’s review of the NuScale SMR design illustrates the substantial complexity of FOAK SMR licencing. Completed in 41 months after docketing, the review required over 250,000 staff hours, assessment of nearly 2 million pages of technical documentation, analysis of 100 GB of test data, and extensive scrutiny by the Advisory Committee on Reactor Safeguards (ACRS) through 40 meetings totalling approximately 440 h (Figure 2) [37]. These demands demonstrate that first-mover SMR licencing can impose significant regulatory, financial and schedule burdens, with potential ripple effects on licencing cost, project timelines and overall commercial viability.

Beyond cost and duration, the review revealed a structural challenge in the USNRC’s existing framework. The absence of a formal dispute resolution mechanism left the regulator without a transparent means of adjudicating technical disagreements where established precedent offered little guidance [37]. This experience shows that novel SMR designs can generate procedural complexities even in mature regulatory environments, implying that newcomer countries may face even greater risks of such challenges unless they proactively incorporate clear mechanisms for resolving emerging licencing issues into their regulatory frameworks.

The transition to modularisation and serial manufacturing introduces further regulatory complexity. Unlike conventional large power plants, SMRs rely on factory-produced modules that are transported to sites for final assembly. This shift necessitates the establishment of in-factory certification processes that enable regulators to inspect and certify integral assemblies prior to shipment [44]. Effective oversight must include robust QA, QC and traceability mechanisms. Yet, because SMR supply chains often involve multiple vendors across different countries, imported modules even if certified abroad remain subject to national licencing requirements where the reactor will operate [45]. This raises concerns about duplication of effort, regulatory fragmentation and the need for greater harmonisation and mutual recognition of certifications.

2.3.3 | Challenges With Review and Assessment

The emergence of SMRs introduces a range of advanced technologies that diverge significantly from conventional large reactors, creating complex challenges for regulatory review and assessment. Developing a robust standard review plan is particularly demanding, as limited operational and regulatory data and applicable standards increase the effort and time required for preparation, review and authorisation [46]. Novel SMR features such as modularity, passive safety systems and distributed configurations pose additional regulatory concerns. Multi-module plants raise questions about operator responsibilities, human factors and accident scenarios where safety functions and resources are shared between modules. Justifying DiD for SMR safety systems, particularly those relying heavily on passive features, requires demonstrating adequate independence between DiD levels. This may involve a combination of passive and active systems alongside inherent SMR safety characteristics validation [47]. However, such demonstrations face several challenges with validation. The limited operational experience means safety demonstrations cannot draw on empirical performance data,

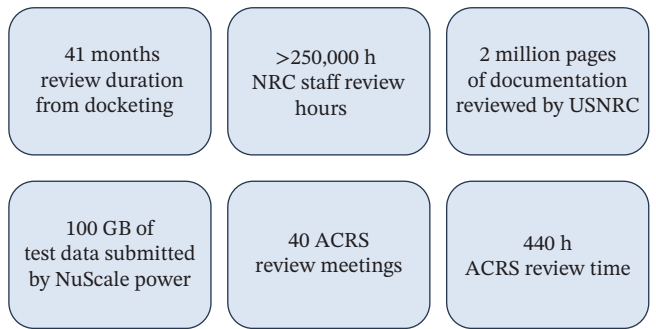


FIGURE 2 | Regulatory effort in USNRC licencing NuScale SMR [37].

forcing regulators to evaluate theoretical models with limited experimental validation. The difficulty in the qualification, reliability and performance assessment of these safety systems under abnormal conditions increases regulatory uncertainties. Additionally, operational considerations such as periodic testing, maintenance, and in-service inspections require further study to ensure ongoing reliability [48]. Collectively, these factors complicate the regulatory review and assessment process, as regulators must carefully evaluate technical justifications for safety without extensive precedents, often necessitating conservative assumptions, additional verification measures and potentially more rigorous oversight compared to conventional reactors.

These technical challenges are compounded by the analytical tools needed to evaluate SMR designs. Existing codes and standards, designed for large light-water reactors, often require significant revision or in some cases, the creation of entirely new ones to adequately address SMR-specific innovations. This challenge is illustrated by NuScale’s development of its own NRELAP5 code, specifically tailored to simulate its SMR design [49]. Regulators must, therefore, acquaint themselves with new tools and methodologies, which becomes increasingly complex if each of the more than 80 SMR designs worldwide requires its own bespoke code. This situation places additional demands on regulatory capacity and extends review timelines.

Importantly, even after an extensive review and assessment process, some SMR-specific technical issues may remain unresolved at the point of certification and instead be managed through unresolved items or licence conditions. The USNRC granted NuScale design certification with three unresolved issues under 10 CFR 52.63(a)(5) due to insufficient information. The shielding wall design in certain plant areas; potential containment leakage from the combustible gas monitoring system; and the ability of steam generator tubes to maintain structural and leakage integrity during density wave oscillations in the secondary fluid system including the analytical methodology for predicting associated thermal-hydraulic conditions, loads, stresses and deformations from reverse flow [40].

The fact that unresolved issues persisted even at the point of certification by one of the world’s most technically mature regulators underscores how genuinely novel and analytically demanding SMR technology remains. For newcomer countries, such gaps pose heightened challenges: without established precedents or regulatory experience, they may face longer review

times, greater resource demands and increased risk of delays or conservatively over-engineered requirements, which can significantly affect project cost, schedule and economic viability.

3 | Regulatory Readiness Assessment Framework for SMRs in Ghana

To support a more systematic evaluation of Ghana’s preparedness for SMR oversight, this study undertakes a comparative assessment based on four key regulatory readiness indicators derived primarily from IAEA [50] GSR Part 1. The assessment focuses on four core dimensions considered fundamental to credible SMR oversight: legal and licencing frameworks, human and technical capacity, financial sustainability and stakeholder engagement (Table 1). These dimensions are examined through practical institutional measures, including the existence of national nuclear legislation, approved regulatory requirements and licencing procedures, staffing levels and role composition, annual regulatory budget and funding structure and the presence of formal stakeholder engagement processes. Collectively, these indicators capture institutional conditions that are central to timely, transparent and technically credible regulation, particularly in the context of FOAK SMR deployment in newcomer nuclear programmes.

3.1 | Legal and Licencing Framework for SMRs

One of the foremost challenges facing Ghana in advancing its nuclear programme particularly in relation to SMRs is the promulgation of its legal and licencing framework. Ghana’s regulatory requirements were originally structured with conventional large-scale reactors in mind. Although the NRA has made progress in draughting regulations, the process of review and promulgating legally enforceable instruments remains slow. By law, all regulations must pass through the Attorney General’s Department and receive parliamentary approval before they are enacted, a lengthy process that delays regulatory certainty and, by extension, the pace of nuclear power development [51]. For SMRs, this delay is especially consequential because their novel features such as modular fabrication, transportable components, and multi-module operation often require design-specific regulatory provisions.

Stage-sensitive benchmarking with other newcomer nuclear states underscores the relative slowness of Ghana’s regulatory

TABLE 1 | Summary of the assessment domains and their associated indicators across four core dimensions.

Assessment domain	Key elements	Key Indicators
Legal and licencing framework	National legislation, regulatory requirements and guidelines	Existence of national nuclear law Approved regulatory requirements and guidelines Existence of regulatory processes and procedures
Human resource and technical capacity	Staff strength and composition	Number of regulatory staff Percentage of staff in technical and non-technical roles
Financial sustainability	Organisational budget	Annual budget of regulatory body Budget composition (government support and internally generated funds)
Stakeholder engagement	Stakeholder engagement framework	Stakeholder engagement requirements, process and procedures.

progression. Türkiye enacted several foundational regulations on nuclear power plant siting, nuclear safety and radiation protection before the nuclear power programme moved into implementation, thereby establishing a regulatory basis in advance of major project milestones [52]. The UAE's FANR, within just 3 years of its establishment between 2009 and 2011, had issued 13 regulations and five regulatory guides, with a further seven regulations and 11 guides at various stages of development [53]. This demonstrates that even at an early stage of programme development, newcomer regulators can generate substantial regulatory output when institutional prioritisation is aligned with programme timelines.

The contrast is further reinforced by the current operational maturity of the FANR and NDK. FANR has published its nuclear laws, regulations, regulatory guides and licencing processes, enabling clearer regulatory expectations and more predictable licencing interactions for applicants oversight [54]. Similarly, NDK has also developed and implemented a more operational legal and regulatory framework supported by an ISO certified integrated management system that signals a higher degree of institutional formalisation and organisational maturity [55, 56]. These comparisons suggest that Ghana's challenge is not simply one of gradual regulatory maturation, but rather one of delayed regulatory conversion. The movement from an enabling statutory framework to a functioning body of enforceable regulatory instruments has proceeded more slowly than in comparable newcomer jurisdictions.

This gap becomes most apparent when Ghana is measured against a mature regulatory jurisdiction that has gone beyond consolidating its framework to actively reforming it for next-generation technologies. The USNRC has not merely maintained an existing regulatory framework but has proactively reformed it to accommodate SMR-specific characteristics. Through 10 CFR Part 53, the NRC offers a risk-informed, technology-inclusive and performance-based optional licencing pathway explicitly designed for advanced reactor concepts [57]. The NRC has introduced a performance-based EP framework specifically designed for SMRs and other new technologies. Major provisions include demonstrating effective response in drills and exercises under emergency and accident conditions; performing hazard analyses of contiguous or nearby facilities to ensure no adverse impact on emergency plans; adopting a scalable approach to determine the size of the plume exposure pathway emergency planning zone (EPZ); and describing ingestion response planning, including offsite capabilities to prevent contaminated food or water from entering the ingestion pathway [58]. This approach exemplifies how regulatory agility, guided by risk-informed and performance-based principles, can reduce barriers for novel reactor technologies. For Ghana, the implication is clear: while the NRA Act, 2015 (Act 895) [59] establishes the statutory foundation for nuclear oversight, credible SMR licencing readiness will ultimately depend on accelerating the promulgation of subsidiary regulations, regulatory guides and licencing pathways capable of addressing design-specific safety, security and operational issues.

3.2 | Human Resource and Technical Capacity

Closely linked to the regulatory challenge is the issue of limited human resource and technical capacity within the NRA. The

authority's mandate spans the regulation of existing radioactive sources in medicine, industry and research, radiation emitting devices and nuclear installations including the current research reactor and the future nuclear power plant [60]. NRA's responsibilities span the full 3S (safety, security and safeguards) functions of nuclear regulation requiring multidisciplinary expertise across a broad and technically demanding regulatory spectrum. Yet it operates with a small pool of professionals, which constrains its ability to implement even the draft regulatory framework once promulgated. As of December 2021, the NRA employed 95 staff, consisting of 65 technical personnel and 30 support staff [61]. This workforce is modest given the breadth and technical depth of its responsibilities, and the situation has been further exacerbated by attrition. In 2022 alone, 17 staff members resigned, reducing total staff strength to 78. Many of those who left were trained nuclear regulatory professionals, highly sought after in both local and international markets [62]. Such attrition weakens institutional memory, disrupts continuity in regulatory development and slows the accumulation of specialised competence in areas such as reactor safety analysis, inspection, review and assessment, safeguards and EP. Efforts to replace these losses are further constrained by public-sector recruitment procedures, which require financial clearance from the Ministry of Finance and Economic Planning, often delayed by competing fiscal priorities.

Contextual benchmarking against comparator newcomer regulators reveals that Ghana's staffing trajectory, while presently modest, is not entirely unusual for a country in IAEA Milestones Phase 2 where the NRA is expected to consolidate institutional capability in preparation for future siting, licencing and oversight functions [10]. In this regard, Ghana's current technical staffing does not appear unusually low for its present stage. Türkiye's nuclear regulatory body reportedly had about 31 technical staff in 2010 at a comparable stage [52], increasing to 73 by 2016 as siting activities progressed [63]. A similar pattern is evident in the UAE's FANR, which grew from approximately 100 staff in 2010 to 160 in 2014 after construction of the first two Barakah units had begun, and further to 249 by 2023. These trajectories suggest that the key issue is not only present staffing adequacy, but whether Ghana has a structured pathway for sustained regulatory growth as technical demands of siting, licencing and future SMR oversight.

Technical Support Organisations (TSOs) can provide specialised analysis, modelling and independent technical review. FANR and NDK has leverage TSOs for their review and assessment task by engaging the Korean Institute of Nuclear Safety (KINS) [64] and NÜTED Nükleer Teknik Destek A.Ş., respectively [65]. However, a regulator itself must retain enough in-house expertise to act as an 'intelligent customer': to define review needs, challenge external advice, make independent judgements, and maintain regulatory accountability. Without this core capability, there is a risk that regulatory authority becomes overly dependent on external actors, potentially weakening institutional learning, continuity and long-term sovereignty in safety decision-making. While TSOs are an important strategic instrument, they are most effective when used to augment rather than compensate for an adequately staffed and technically competent regulator.

Currently, established regulators such as the CNSC operate with a substantially larger institutional base, with approximately 968

staff, of whom about 72% are technical personnel, including engineers and scientists [66]. Türkiye’s NDK has been reported to have around 218 staff [65], while the United Arab Emirates’ FANR has approximately 249 [67]. Staff composition adds further nuance: Ghana’s NRA has the highest proportion of technical staff (79%), compared with NDK (74%), CNSC (67%) and FANR (45%) (Figure 3). This indicates a Ghana’s deliberate emphasis on technical staffing. However, the small overall workforce means that this high proportion does not translate into strong absolute technical capacity. Ghana, therefore, appears technically concentrated but institutionally thin, despite carrying a broad mandate across radiation and nuclear applications.

3.3 | Financial Sustainability of Regulatory Activities

The financial sustainability of the NRA remains a central consideration in Ghana’s preparedness to regulate SMRs. Although the NRA has established a functioning regulatory framework, the scale and structure of its funding suggest important constraints in relation to the expanded regulatory demands associated with SMRs. Unlike conventional large nuclear power plants, SMRs introduce additional regulatory complexities, including oversight of modular and factory-based construction, assessment of diverse and often FOAK reactor technologies, multi-module operational interfaces and safeguards considerations for transportable or replaceable units [27], all of which demand specialised expertise and analytical tools. Based on the available figures from the Ministry of Finance and Economic Planning [68], NRA’s 2025 budget was approximately GHC 18,149,267 (~US\$1.67 million) [69] of which approximately half is funded by the Government of Ghana. While this mechanism has sustained basic operations, it is insufficient to finance the extensive capacity-building, advanced training, acquisition of state-of-the-art analytical codes, stakeholder engagement and the development of new licencing frameworks required for effective SMR regulation. This limitation becomes clearer when compared to the 2025 annual budget of FANR and CNSC. The UAE’s FANR operated with a budget of approximately AED318 million (~US\$86.6 million) [70] in 2025, while Canada’s CNSC [71] had a budget of CAD199,684,684 (~US \$145.4 million) for the 2025 fiscal year.

From a financial sustainability perspective, the 2025 budget composition of the three regulators reveals important differences in institutional financial resilience. In 2025, Ghana’s NRA was

financed approximately equally through government budgetary support and internally generated funds (IGFs), with each contributing about 50% of the authority’s total budget. This indicates some capacity for cost recovery, but also a substantial reliance on public financing. By comparison, FANR is financed 90% through its own revenue and 10% by government [64], while CNSC [72] is financed 70% through self-generated revenue and 30% through government appropriation (Figure 4). The 50:50 composition of the NRA budget is understandable in a newcomer context, where the domestic nuclear sector is still developing and the volume of licensable activities is not yet sufficient to generate robust cost recovery. However, it also implies that the authority’s self-financing capacity may remain constrained until a larger and more mature nuclear and radiological market emerges. This indicates that, beyond its relatively limited absolute budget, the NRA-Ghana also remains less financially self-sustaining than comparator regulators such as FANR and CNSC. With approximately 50% of its funding dependent on government budgetary support, the authority remains vulnerable to fiscal constraints, budget reprioritisation or broader macroeconomic shocks that may affect public expenditure. In contrast, the higher cost-recovery shares of FANR and CNSC suggest greater institutional financial resilience and operational autonomy in supporting long-term regulatory preparedness and effective independent decision-making.

3.4 | Stakeholder Engagement and Public Confidence

As a newcomer country, Ghana faces the added challenge of building trust and confidence in its ability to regulate nuclear power, particularly SMRs. While the NRA has experience regulating a research reactor, public expectations and scrutiny surrounding a FOAK SMR deployment are significantly higher. This scepticism is not limited to Ghana; even in established nuclear power countries [73], doubts persist about the safety and regulatory oversight of SMRs due to the lack of extensive operational and regulatory history [74]. Past nuclear accidents and the decisions of some nations to scale back or phase out their nuclear programmes have amplified public concern globally [75]. For Ghana, these global apprehensions compound the local perception that the NRA may not yet have the institutional maturity to credibly regulate a nuclear power plant [76]. To strengthen preparedness, the NRA has established important collaborative

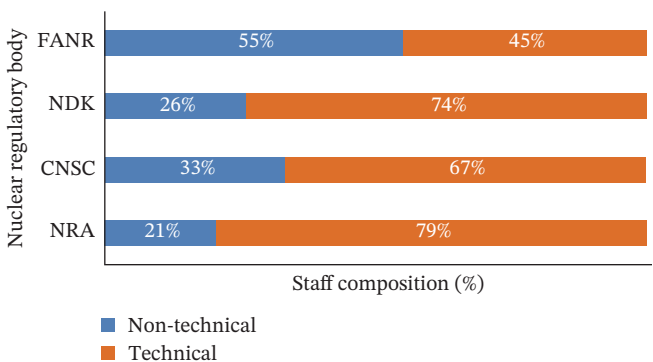


FIGURE 3 | Comparative staffing composition of selected nuclear regulatory bodies.

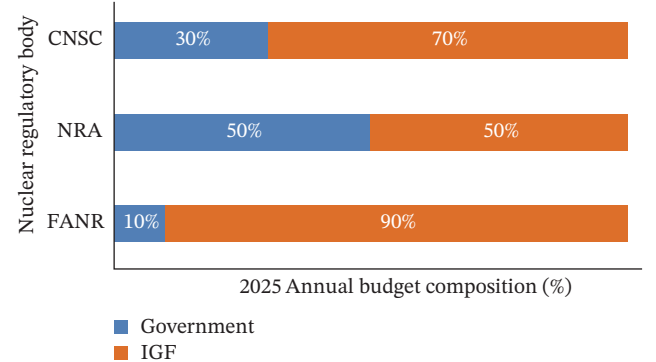


FIGURE 4 | Comparative budget composition of selected nuclear regulatory bodies.

arrangements with other state institutions such as the Environmental Protection Agency [77] and the Petroleum Commission to clarify responsibilities and strengthen oversight. In the area of nuclear security, the NRA collaborates with allied institutions through the Nuclear Security Committee, co-chaired by the Nuclear Security Coordinator and the Director-General of the NRA. It also works with the National Disaster Management Organisation (NADMO) on nuclear EP and response, and with the Ghana Immigration Service on the control of nuclear and radioactive materials across borders [78]. These cooperative mechanisms create an integrated, multi-agency framework that enhances safety, security and regulatory preparedness.

The USNRC demonstrates a more mature and institutionalised model of stakeholder engagement than is currently evident in Ghana. In the United States, public participation is legally embedded in the licencing process under 10 CFR 2.309, which provides for public notice, hearing requests and petitions to intervene in licencing actions. This creates formal opportunities for stakeholders to contribute to safety and policy discussions [79]. The receipt of approximately 36 written stakeholder position papers between 2010 and 2020, many focused on SMR-specific issues such as source term analysis, licencing structure, decommissioning and EPZs, demonstrates active and technically informed public involvement [80]. In comparison, public participation in nuclear governance in Ghana remains relatively limited and is largely characterised by occasional awareness initiatives rather than fully institutionalised engagement processes. The current legal and regulatory framework does not yet appear to provide explicit and structured provisions for community consultation, grievance redress or sustained stakeholder engagement across the lifecycle of nuclear projects [81]. This gap may increase the risk of public mistrust, delays or resistance, particularly in relation to high-consequence decisions such as siting, reactor operation, radioactive waste management and decommissioning.

The CNSC also reflects a highly structured and well-resourced approach to stakeholder engagement that extends beyond general public information into formal participation and capacity support. Its framework includes regulatory consultations on proposed regulations and guidance, participant funding for licencing and environmental assessments, an indigenous and public capacity fund and established engagement protocols for long-term collaboration with indigenous nations and communities. The CNSC [82] also maintains regular dialogue platforms such as its Environmental Groups Forum. This illustrates that stakeholder engagement in nuclear regulation is most effective when it is institutionalised as part of the regulatory system. Essentially meaningful stakeholder participation in nuclear regulation depends not only on transparency, but also on procedural access, sustained dialogue and financial support for informed engagement. Ghana's stakeholder engagement capacity is closely influenced by the current scale of financial resources available to the NRA. Effective communication on SMRs requires sustained investment in public outreach, risk communication, community consultation, media engagement and transparency mechanisms. Given the authority's relatively limited budget, these activities may understandably remain incremental rather than fully institutionalised. Strengthening financial support for such functions would enhance public confidence-building efforts and contribute to broader societal acceptance of future SMR deployment.

4 | Opportunities and Strategic Pathways

4.1 | Modernisation and Harmonisation of Regulatory Framework

Although the current draft status of Ghana's nuclear regulations presents a near-term constraint for SMR licencing, it also creates a strategic opportunity for NRA to modernise its framework before formal finalisation. Rather than adapting legacy requirements developed primarily for large, site-built reactors, Ghana can incorporate contemporary international guidance and emerging good practices specifically relevant to SMRs. Given the wide range of SMR designs under development, tying the regulatory framework too closely to the technical features of a specific reactor type could make it outdated as the SMR market changes. A technology-neutral, risk-informed and objective-based framework therefore offers a more practical and durable approach. Such a framework places greater emphasis on demonstrating that safety objectives are met, rather than on compliance with fixed technical design rules. However, for this to work effectively, the NRA must clearly define the safety objectives to be met and develop the internal technical capacity or TSO to evaluate diverse safety case arguments presented by different vendors.

A priority regulatory development pathway should therefore focus on finalising core regulatory requirements in a phased manner. In the short term (1–12 months), the NRA should prioritise the formal approval of key regulatory instruments that are most critical to the early phases of a nuclear power project. Since nine draft regulations are currently under parliamentary review, a practical strategy would be to expedite those with the greatest immediate relevance to SMR pre-licencing and early licencing activities. These include regulations on siting of nuclear installations, integrated management systems, basic ionising radiation control, EP and response, nuclear security and safeguards and the design of nuclear installations. Prioritising these regulations would provide an essential legal and procedural basis for early vendor engagement, site evaluation, preliminary safety submissions and design certification activities. This phased approach would allow Ghana to establish regulatory certainty in the most time-sensitive areas first, whilst continuing to refine supporting guidance and secondary process documents in parallel.

Beyond formal approval of regulations, the NRA should develop graded approach documentation to support proportionate review and decision-making across different SMR technologies, hazard profiles and deployment models. This should be complemented by a clear policy and process for long-lead items, particularly where safety-significant components may be procured, manufactured or inspected before a full construction licence is granted.

Regional regulatory harmonisation through platforms such as the Forum of Nuclear Regulatory Bodies in Africa (FNRBA) offers a practical pathway to reduce avoidable duplication in review and assessment. Joint reviews, collaborative assessments and selective leveraging of credible prior reviews can reduce the burden of reassessing certain aspects of a design already examined in depth elsewhere. Similarly, structured engagement with vendor-country regulators can help Ghana benefit from existing technical evaluations of licenced designs. However, such cooperation should not be interpreted as automatic acceptance of foreign licencing decisions. The NRA remains responsible for certifying any nuclear installation proposed in Ghana, and

harmonisation should serve as a mechanism for informed reliance and knowledge transfer rather than the imposition of external authority.

4.2 | Capacity Building and Technical Support

The effective regulation of SMRs in Ghana will depend fundamentally on the NRA's ability to build, retain and progressively deepen a technically competent workforce. While external TSOs, vendor-country regulators and international partners can provide valuable short- to medium-term support, long-term regulatory credibility requires a deliberate strategy to strengthen internal expertise. In particular, the NRA should maintain a minimum core of in-house specialists capable of acting as an 'intelligent customer', that is, professionals who can understand, challenge and independently evaluate the technical analyses and recommendations submitted by TSOs, vendors and consultants.

A practical first step is the development of a formal, competency-based SMR regulatory training and workforce development plan for NRA staff. This should be informed by a structured training needs assessment that maps the technical and regulatory competencies required across the full regulatory lifecycle, including licencing, review and assessment, inspection, safeguards, EP and oversight of digital instrumentation and control systems. The training plan could combine in-house instruction, external specialist courses, secondments, peer-learning opportunities and technology overview modules, ensuring that staff receive the right training at the right time. Training should initially focus on broad SMR fundamentals and regulatory principles, then progressively expand to include specific technologies under consideration in Ghana, proportionate to the maturity of the design information available. To complement training, the NRA should institutionalise mock licencing reviews, joint technical assessments with partner regulators and targeted research collaborations with universities and specialised institutes. These activities can reveal capability gaps early and help prioritise recruitment and development in areas such as passive safety analysis, probabilistic and deterministic safety assessment, digital instrumentation and control, modular manufacturing oversight, and transport safety for factory-fuelled or sealed reactor units.

Ghana should consider a more structured recruitment and retention framework that supports technical career progression, performance-based development, postgraduate study support and competitive non-salary incentives such as retention allowances for scarce skills and sponsored professional certification where feasible. Measures such as continuous professional development, recognition schemes, flexible working arrangements and clear succession planning can improve staff continuity. Over time, this blended approach can reduce external dependence and strengthen the NRA's institutional readiness to regulate FOAK SMR technologies with confidence and consistency.

4.3 | Pre-Application Engagement With SMR Licence Applicants

Pre-application engagement between the NRA, potential SMR licence applicants and technology vendors provides a critical platform to clarify regulatory expectations, address information gaps and establish a collaborative approach to safety before

formal licencing begins. For a newcomer country such as Ghana, where the regulatory framework is still evolving and performance-based approaches are increasingly emphasised, the effectiveness of such engagement depends not only on willingness to interact early but also on the existence of clear policy, processes and procedures to govern it. Some SMR designs cite features such as smaller reactor core inventories, underground siting for enhanced physical protection and advanced passive safety systems as justification for reducing or even eliminating conventional containment structures. The NuScale SMR design, for instance, proposes reducing the EPZ to the plant site boundary: just a few 100 m compared to the traditional 10-mile radius for large nuclear power plants [83]. For newcomer regulators, however, these claims demand rigorous safety justification and extensive experimental evidence before approval, given the implications for public and environmental protection. Pre-licencing engagement therefore offers a structured avenue to define the scope, timing and technical parameters of required demonstrations and safety tests before formal submissions. This is especially valuable for FOAK SMRs, where diverse designs, limited operational and regulatory experience increase licencing complexity. Addressing issues such as site evaluation criteria, safety analysis methodologies and EP requirements at the pre-application stage can streamline licencing reviews, improve transparency and strengthen public confidence in regulatory oversight.

4.4 | Public Awareness and Stakeholder Engagement

Beyond technical capacity, public acceptance remains a critical determinant of success for nuclear power programmes, particularly for newcomer countries deploying FOAK technologies such as SMRs. Global scepticism surrounding nuclear safety shaped by past nuclear accidents underscores the need for proactive, transparent and sustained stakeholder engagement. Although Ghana's NRA has initiated awareness activities, including training journalists on nuclear reporting and participating in government-organised visibility webinars, these efforts must be expanded and institutionalised to build enduring trust in nuclear safety regulation.

A strategic, staged approach to stakeholder engagement is essential. Beginning with basic information-sharing and moving toward inclusive decision-making, the process should enable communities, policymakers and civil society actors to participate meaningfully in nuclear energy discussions. This progressive model, illustrated in Table 2, outlines five stages: inform, consult, involve, collaborate and empower each representing deeper levels of public participation and trust-building.

This structured approach ensures that communication efforts evolve beyond one-way information dissemination toward deeper collaboration and empowerment. By institutionalising the five-stage engagement continuum, the NRA can build public trust, foster transparent decision-making and secure the social acceptance necessary for the successful deployment of SMRs in Ghana. Such a framework will not only demystify nuclear technology and address lingering safety concerns but also demonstrate the regulator's commitment to openness, accountability and public safety.

TABLE 2 | Five-stage public engagement continuum for SMR deployment in Ghana [84].

Stage	Activities
1. Inform	- Publish regular updates on NRA’s website - Issue e-bulletins - Share information through social media platforms - Distribute informational materials via newsletters, press releases and local media channels
2. Consult	- Organise public consultations and public hearings - Attend nuclear new-build community meetings - Run online public comment processes - Listen to NGO concerns at nuclear liaison forums.
3. Involve	- Establish citizen advisory committees - Create stakeholder forums near potential nuclear sites - Facilitate participatory decision-making discussions with local communities and civil society groups
4. Collaborate	- Partner with developers, NGOs and local authorities on planning consultations - Jointly host national stakeholder workshops, webinars and conferences to co-develop strategies and solutions
5. Empower	- Explore participatory budgeting mechanisms or community-led initiatives - Ensure stakeholder recommendations influence final policy and regulatory decisions where appropriate

5 | Conclusion

This study finds that Ghana has established a meaningful foundation for nuclear regulation, but further strengthening will be required before it can confidently licence and regulate the deployment of SMRs. The existence of a national nuclear law, an operational regulatory authority and prior experience in research reactor oversight provide a credible institutional starting point. However, current readiness remains partial and transitional, rather than sufficient for the safe and independent regulation of a FOAK SMR project.

The most critical regulatory gaps identified in this study relate to the draft status of key regulations and licencing process documents, limited in-house technical capacity for advanced reactor review, constrained financial sustainability and still-developing mechanisms for stakeholder engagement.

Before SMR deployment can be safely licenced in Ghana, several priority actions are required. First, the NRA should finalise and operationalise core regulations and processes particularly those related to siting, design and construction, while adopting a risk-informed and technology-inclusive framework supported by graded regulatory approaches. Additionally, the NRA should strengthen internal technical competence through structured SMR-specific training, targeted recruitment, retention measures, mock licencing exercises and strategic use of TSOs, whilst maintaining sufficient in-house expertise to act as an ‘intelligent customer’. Sustainable funding mechanisms must be enhanced to support long-term regulatory financial independence, specialist capability development and acquisition of analytical tools. Finally, early stakeholder engagement, transparent communication and regional and international regulatory cooperation should be institutionalised to support public confidence and reduce avoidable duplication in review and assessment.

Overall, Ghana’s regulatory readiness for SMRs may be characterised as foundational and progressing, with important institutional elements already in place but further development still needed in key areas. With timely approval of key regulations and licencing processes, stronger technical and financial capacity in the NRA and more structured stakeholder engagement, Ghana can build a credible foundation for the safe oversight of SMR deployment.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are available upon request from the authors.

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