



SMR Current Status: Development Needs and Global Perspectives

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Changing the World's Energy Future

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SMR CURRENT STATUS: DEVELOPMENT NEEDS AND GLOBAL PERSPECTIVES

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Abstract

Defined as nuclear reactors with a power output up to 300 megawatts electrical (MWe) by the International Atomic Energy Agency (IAEA) and targeted for multipurpose applications, small modular reactors (SMRs) have been recognized as a very promising, clean, affordable, and sustainable energy source by many countries. At present, more than 80 SMRs are under design, development, demonstration, deployment, and beyond (4D+) phases worldwide. This paper focuses on the current world status of SMRs and focuses on the necessary developments to accelerate the process of adopting SMRs as a major energy source globally. SMRs are not a new concept, but they do represent a new vision for older concepts if the challenges inherent within them are mitigated with strategic and realistic solution approaches. The major challenges for SMRs 4D+ like any new reactors are: (a) qualifying the advanced fuel-to-reactor design; (b) supporting rapid scaled/prototypic experimentations; (c) maintaining local and global codes, standards, and licensing; (d) supply chain issues; (e) effective cradle-to-grave nuclear fuel cycle and fuel material transportation, and (f) mitigating financial and environmental risks. These upfront challenges can be mitigated with a synergistic solution approach among the various stakeholders: industry, academia, research, government, and international entities.

Keywords: small modular reactor; 4D+ phases, simpler system configuration, and next generation energy systems

1. INTRODUCTION

Although most reactors in the operational nuclear fleet have megawatt capacity ranges (most with a unit capacity of over 500 megawatts electrical [MWe]), global interest in reduced-sized/capacity reactor designs and development has grown. The increased costs of construction material, labor, and management ultimately have increased the installation costs of gigawatt-sized reactors. Thus, small modular reactors (SMRs), which the International Atomic Energy Agency (IAEA) defines as nuclear reactors whose power output is under 300 MWe, are proving to be a very promising alternative for many different countries, regions, and industries around the world [1]. Despite the recent surge in interest, the basic SMR concept is not a novel one. Initial plant designs in the 1950s—including the very first commercial reactors—were, in many ways, SMRs with power output ranges of 10–100 MWe [2]. In the 1960s, newly constructed nuclear reactors had power output ranges of 100–300 MWe. Considering the economy of scale with fewer components, by the 1970s, the nuclear industry had developed larger reactors of mostly gigawatt capacity (i.e., 1000 MWe and higher) [2]. But these large-capacity reactors entail various challenges, including construction delays, cost overruns, lengthy and challenging regulatory approval processes, and supply chain issues. These challenges became more prominent after the Fukushima Daichi nuclear

accident due to rising concern for enhanced safety and redundant systems. However, smaller capacity reactors without these same challenges, have started to gain more interest [2].

SMRs show promise as an alternative to large-capacity reactors, due to features like smaller size, added safety, simpler system configuration, and an accelerated design process. The fact that SMRs have simpler system configurations and safety functions reducing construction times/costs in comparison to gigawatt-sized reactors is a major draw. Over 80 SMRs are currently undergoing design, development, demonstration, deployment, and beyond (4D+) phases worldwide, with varying design features. Thus, understanding the design features and unique development needs of each SMR is pivotal for successful licensing efforts. The required R&D—maintaining codes and standards—should focus on a global perspective, rather than a local-, regional-, or country-specific one, along with the user expectations, regulatory requirements, and legislation involved.

SMR technology should emphasize safety first as the critical enabling characteristic with economics as its second. Like other new reactor technology development, SMR design and development should consider the standard safety principles and considerations. Specifying safety goals as a design target and ensuring fail-to-safe status is a much desirable end-state. A multi-layer defense-in-depth safety strategy, adequate safety functions, safety barriers, and safety margins to minimize the potential dangers from inadequacies in design or operation are also crucial. Best estimate plus uncertainty analysis, as well as an integrated risk-informed decision-making strategy needs to be incorporated as well. The primary overall target is to ensure safety to people, facilities, and the environment.

This paper focuses on the current global status of SMRs, particularly the developments needed to accelerate the global adoption of SMRs as a major energy source. Many of the challenges and needs in SMR development are similar to those for any 4D+ process in new reactor systems. These needs are focused on qualifying the fuel-to-reactor design, scaled testing, meeting regulatory requirements, resolving supply chain issues, specifying fuel cycle and transportation, and lessening financial and environmental risks. Other challenges to nuclear power programs may be affected by socioeconomic and political issues, which are in many cases country- or region-specific but may impact large-capacity and small-capacity reactor systems differently.

2. STATUS OF SMR WORLDWIDE

The IAEA provides its member countries with updates—through reports, books, and its webpage—on SMR designs, applications, and development progress. SMR designs vary in terms of target application, reactor type (e.g., fuel type, coolant type, power conversion type), safety system (e.g., active, passive, hybrid), fuel cycle, and plant layout. Only two SMRs have ever made it to the final construction and initial operational phases: (a) the Russian-Federation (RF)-developed floating power SMR, KLT4S, which began commercial operation in May 2020; (b) a high-temperature gas-cooled SMR developed by China that recently began commercial operation [2]. CAREM, an integral pressurized-water reactor (i-PWR)-type SMR developed by Argentina, which was scheduled to begin its civil construction in 2024, but since has been delayed due to several challenges [2][3].

2.1. Reactor technology development roadmap

As mentioned earlier, the reactor technology 4D+ roadmap takes years-to-decades to complete and generally involves various phases. SMRs are no exception, but vendors must maintain their commitments to cost and schedule. Near-term technology development can be accomplished by adopting or buying existing technology. However, long-term development is required for innovative design ideas, which entail detailed design, testing, analysis, and licensing. Only two SMRs (i.e., RF's KLT4S, China's HTR) have entered their initial years of operation. Construction on several other designs (e.g., CAREM, GE-Hitachi's BWRX-300) are scheduled to be completed within this decade [2]. By 2030, other design certifications are likely to follow.

2.2. Nuclear power program milestones

As seen in Fig. 1, the IAEA nuclear power program has several milestones consisting of three phases [4]:

- **Up to Phase 1:** This includes initiating the national nuclear power program—as part of the national energy strategy—and planning for the country's first nuclear power plant (NPP), including Milestone 1, the project feasibility study.

- **Phase 2:** If the NPP project proves feasible, Phase 2 entails completing preparations for constructing the NPP, followed by Milestone 2, inviting bids for the NPP.
- **Phase 3 and beyond:** This entails constructing the NPP and completing Milestone 3, plant commissioning. The final stage and milestone are to begin successful operation of the plant.

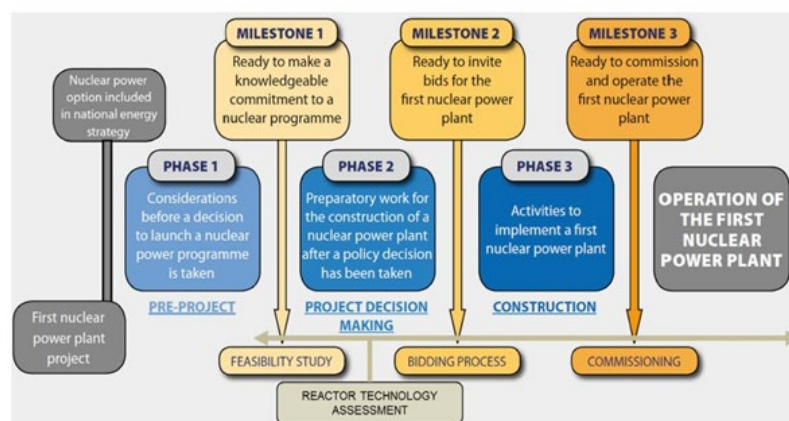


FIG. 1. Nuclear power program and reactor technology assessment and deployment phases and milestones [4].

2.3. Reactor technology competitiveness, challenges, and prospects

Reactor technology economic competitiveness is estimated and compared based on the levelized cost of energy/electricity (LCOE) and overnight construction cost (OCC). Comparisons with other energy forms are limited due to variable subsidies, environmental impacts, and waste management. This enables the estimation of a project's financial risk, which largely varies when comparing gigawatt reactors and SMRs. Large-capacity reactors entail the following unavoidable challenges, which make SMRs more competitive, as listed below:

- **Construction delays leading to increasing costs:** As with other megaprojects, massive NPP projects suffer from construction delays and the resulting cost overruns.
- **Lengthy and challenging regulatory approvals:** Large-capacity reactors entail stringent difficulties at each regulatory approval stage, due to the larger impact stemming from their capacities.
- **Supply chain challenges:** Obtaining the required materials (e.g., fuel, nuclear sensors, instruments) and components (e.g., fuel, reactor pressure vessel, reactor coolant pump) requires a longer timeframe than for other heavy industrial components and materials.

2.4. SMRs technology, types, and designs overview

The IAEA lists six broad categories (or types) of SMR designs. Depending on the given reactor design, certification will require scaled experimental data to validate the models and correlations used for reactor licensing. Each reactor type corresponds to its own set of opportunities and challenges. The potential applications for these six SMR types are as follows:

- **Land-based, water-cooled:** These reactors are expected to reflect technologies similar to those found in the existing reactor fleet; therefore, these are the most mature of reactor technologies. Water-cooled SMRs come in the form of PWRs, boiling-water reactors (BWRs), and CANDU-SMR.
- **Marine-based, water-cooled:** This PWR type would most likely avoid operational challenges that arise during submersion because of fluctuations in void fraction and reactivity.
- **High-temperature gas-cooled:** An excellent candidate for industrial process heating applications extending beyond simple electricity generation.
- **Fast neutron spectrum:** This category is dominated by liquid-metal-cooled reactors, due to their compactness and higher degree of coolant heat transfer. Their deployment will be challenging because of low technology readiness levels (TRLs) and lack of industry-grade component availability.
- **Molten-salt:** These reactor types may be a good candidate for design innovations, but the reactor materials, fuel, and coolant behavior are likely to present challenges.
- **Micro-sized:** Movable or transportable, mostly for off-grid applications, such as for defense-based applications, remote islands, and disaster relief management.

3. SMR DEVELOPMENT NEEDS

Many SMRs are currently undergoing design and development phases at various companies and in different countries, including newcomer nuclear companies. However, only a few have attained design and development certifications. Numerous challenges arise in designing and developing new reactor systems and technologies, as most design information is proprietary, and thus not available in the open literature.

The general SMR challenges are related to new technology, complex engineering tasks, reliability issues, economic viability, licensing, and regulatory issues [5]. Subki [6] used expert surveys to categorize and rank the major challenges for SMR deployment as shown in Fig. 2. The priorities that are indicated include: (a) necessary regulatory and licensing changes, (b) economics, (c) instruments and control, and (d) proliferation resistance.

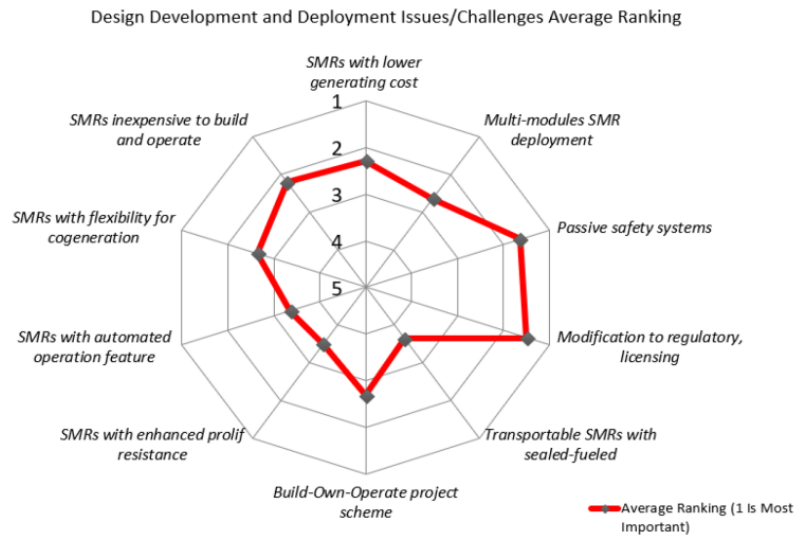


FIG. 2. Ranking major deployment challenges [5].

Furthermore, to be market-competitive, the newcomers must also showcase innovative features while simultaneously reaching higher TRLs—something that requires adequate resources in the form of money, materials, manufacturing capabilities, and expertise. Therefore, understanding the primary needs for accelerating SMR 4D+ is essential, as discussed in the sections that follow.

3.1. Qualifying the advanced fuel-to-reactor design

Reactor design and analysis requires continuous effort to qualify the proof-of-concept and first-of-a-kind design via adequate modeling and simulation (M&S) and scaled experimentations (e.g., integral effect testing, separate effect testing) for reactor and fuel systems. For a new nuclear fuel material, the time required from fuel material identification to passing the qualification process—including irradiation testing in qualified facilities under prototypical conditions, post-irradiation examinations, and regulator performance evaluation—is estimated to be 20 years in the United States (U.S.) [7]. Thus, many SMR conceptual designs consider matured fuel materials, with final-state R&D being conducted to commercialize them. Examples of such cases are tri-structural isotropic (TRISO) particle fuel, high-assay low-enriched uranium (HALEU) fuel, and accident-tolerant fuel (ATF) concepts. Nuclear fuel material research is restricted based on fuel enrichment (e.g., enrichment of civil and research reactors should be within 20%) and contains proprietary information.

The reactor design analysis considered integrated design for neutronics, thermal-hydraulics, and structural analysis that involved various computer code and multiphysics computational tools/codes at various time and length scales. System code and multiphysics M&S tools are used for system-level to component-level design analyses, whereas subchannel and continuum-level codes are used for coolant flow channel, fuel material thermal-safety programmatic and safety analysis for a specific region of interest. Nuclear energy newcomer countries, in many cases, will find it hard to resolve the new nuclear fuel qualification, nuclear waste storage, and disposal challenges due to lack of legislation and infrastructure to enable new SMR development. However, the use of proven or high TRL reactor and fuel technologies and R&D support could minimize these challenges.

3.2. Supporting rapid scaled/prototypic experimentations

Reactor system design and analysis requires appropriate use of M&S tools, and qualification of those tools and models, including verification and validation against scaled experimental datasets, is pivotal to ensure design qualification. It is pivotal to ensure the scaled-facility test data supports the Evaluation Model and Development Assessment Process (EMDAP) specified by the NRC Regulatory Guide (RG) 1.203 [8]. Development of a scaled test facility starts with a phenomenon identification and ranking table (PIRT) study that includes identifying phenomena of interest (POI), ranking the POIs and states-of-knowledge (SOKs) in terms of importance (i.e., high, medium, or low), and determining the figures of merit (FOMs). Based on the POI rankings and SOK, it is necessary to implement an evaluation model (EM) development and assessment process to prepare licensing documentation based on adequate experimentation data, EM verification and validation, and scaling results. In most cases, recommendations stemming from the regulatory review will necessitate justification or revision of the EMs to obtain final design approval confirmation. The important FOMs for reactor design and licensing requirements are peak cladding temperature, maximum cladding oxidation, and maximum hydrogen generation; the core geometry remains coolable; and the containment pressure and temperature for shutdown/safety cooling is set to remove decay heat at a certain period, thus maintaining the regulatory codes and standards.

3.3. Maintaining local and global codes and standards, and meeting regulations

The primary need for a nuclear program is an effective, credible, and trusted regulatory body. The regulations must include requirements that clearly identify the design criteria licensees must comply with, but the regulator must also be prepared to communicate expectations to licensees regarding compliance with the requirements, including the implementation of codes and standards. The consensus-based approach to the development of codes and standards over the past several decades for the current NPP fleet have proven to be successful and of value in achieving a technically sound means of compliance with national and international regulations. However, the basis and context of these standards may pose challenges for many SMR designs, particularly advanced reactor (AR) designs. This is primarily the result of either a focus of most codes and standards on the more commonly used light-water reactor (LWR) technology or a need to revise existing codes and standards such that they support AR design licensing needs.

Preparations for the development and implementation of codes and standards to support the deployment of SMRs have commenced in North America. Some achievements have been made through recent issuance and regulatory endorsement of key standards specific to the commercial nuclear power industry that can apply to multiple reactor designs and technologies. In an effort to enable a more efficient deployment of AR designs, North American standards design organizations have initiated actions to address recently identified gaps in codes and standards that can be used for the design and operation of SMRs around the world.

Actions being taken extend beyond the deployment of reactor technologies solely for commercial nuclear industry use, encompassing nuclear technologies applicable to space or other supporting areas, such as reactor siting and operations. Codes and standards development will be inclusive of multiple reactor types and technologies that will assist in the efficient deployment of the multitudes of SMR designs anticipated for the future. It is important to understand the recently issued codes and standards benefiting SMR deployment and summarize planned actions and to address identified gaps in codes and standards, supporting SMR and AR technology deployment.

The need for continual support in the creation of regulations specifically aimed at SMR and non-water-cooled reactors extend beyond design and operation. Factors such as site impact are less relevant to SMRs than to large reactors, whose resulting environmental footprint differ from that of normal commercial reactors. Thus, regulations are being looked at and worked on to enable SMRs to obtain site (including multi-sites for transportable micro-reactors) and multi-unit capacity addition approvals in a timely fashion.

3.4. Resolving supply chain issues

Addressing supply chain issues in SMR deployment is paramount to moving this technology to the forefront of the nuclear industry, which currently faces several such issues. For one, the supply chain cannot keep up with production demands for modular fabrication, which is an important aspect of many SMR designs. Nuclear industry partners and stakeholders need to work together to review regional fabrication capabilities and fill in the

production gaps accordingly. The current supply chain must be adapted to include SMR production capabilities and to increase the capacity to fulfil industry demands.

Many SMR designs incorporate novel materials that may not be currently approved by design standards and regulating authorities (e.g., graphite, helium, molten salts, beryllium) resulting in challenges in fabrication of key portions of some SMR designs exacerbating supply chain issues. Developing a means of deploying these novel materials that is significantly shorter than current qualification processes will help streamline the process of obtaining and implementing these materials, as well as increase their availability. Associated special manufacturing techniques and processes for constructing reactors using these materials and unique components must also be commercialized.

3.5. Cradle-to-grave nuclear fuel cycle, including transportation

It is necessary to ensure innovative but effective strategic and legislative commitments for the cradle-to-grave nuclear fuel cycle, including transportation. Nuclear reactor technology considers cradle-to-grave policies, legislation, and regulation. The following steps are involved in the decades-long reactor life cycle: reactor design and development, operation, and decommissioning. Each stage requires specific regulatory approval and decision-making efforts.

The fuel cycle must also be considered. With the advent of new SMR types, new types of advanced fuels are also being brought to the table. Fuels such as HALEU (enriched at 5%–20%) and TRISO fuels (based on a UO₂/UCO fuel kernel) have already been tested in various conditions; however, these tests should still be continued specific to the SMR designs envisaged to operate using these fuels. Many AR designs are made smaller by utilizing HALEU to get more power per unit of volume. Research and development funding must be cultivated around the idea of novel reactors and fuels.

3.6. Mitigating financial, environmental, and other related risks

The challenges associated with large-capacity reactor deployment are mostly economic in nature: high-capital investment, construction delays, and project management complexity. Smaller projects have faster learning curves exercised more often making the learning more beneficial. The prospects/benefits of SMRs over large-capacity reactors, provided justification for reduced financial risks associated with SMRs due to:

- Lower chances for construction delay and cost overrun due to factory fabrication
- Reduced time and cost from an nth-of-a-kind engineering plant and reduced cooling requirements
- Reduced supply chain challenges for smaller size components that are suitable for SMRs and smart grids
- Suitable for coal-to-nuclear and nuclear-to-nuclear by replacing coal/old-reactors with SMR.

The environmental risks associated with large-capacity reactors come in the form of requirements pertaining to natural resources, fuel inventories, and impacts that occur both during and after a potential accident. The following solution strategies reflect the benefits of SMRs over large-capacity reactors:

- Less land, water, materials, and auxiliary systems are required. Feasibility studies, site selection, and potential relocation are simple, effective, and less dependent on natural resources.
- The reduced fuel inventory minimizes containment challenges during any technological or natural catastrophe. A smaller-sized emergency evacuation zone can meet the reactor licensing requirements.
- Making the reactor in the factory and transporting it to the site by large truck, train, or ship. No construction hazards would be presented by the reactor site.

However, there still are risks associated with SMRs that should be noted—including but not limited to new technologies that may result in longer environmental assessment/regulatory review timelines, which may impact cost/schedules; supply chain limitations that may impact cost/schedules (e.g. limited suppliers to manufacture reactor vessels and limited fuel supply); and environmental risks associated with the transportation of reactor vessels/fuels in remote communities.

3.7. Other sociopolitical and legislative challenges

Studies also show that various factors dictate decisions to maintain scrapping, suspension, or deferral positions of nuclear power programs, such as energy, economics, and environmental issues. Other factors include

political commitments, government/military alliances with nuclear supplier countries, and major nuclear accidents. Approaches to strategic solutions include:

- Most country-specific nuclear energy decisions are based on electricity demand, energy pricing, economic conditions, and sustainability goals. As SMRs require less of a financial commitment and can be deployed quickly, this could lead to a low-payback period, thus making the value proposition even more attractive.
- SMRs require shorter deployment times, and thus have a lower probability of construction delay and cost overrun as compared with large conventional LWRs.

4. CONCLUSION

The development of advanced SMRs is currently ongoing. These new reactors are being designed by prioritizing customer needs with an accelerated innovation in 4D+ by minimizing engineering, regulatory, and economical challenges. The following characteristics were highlighted:

- SMRs are not a new concept; however, SMRs adopt an optimized economic scaled design for rapid deployment. Several SMR designs are in the process of obtaining design approvals.
- Addressing SMR regulatory challenges will support broader nuclear innovations, including Generation IV designs. While financial hurdles are common, SMR vendors must adhere to cost and schedule commitments for customers and regulators.

Worldwide, more than 80 SMR design concepts are in various design and development stages. Therefore, understanding the status of those designs and their prospects, challenges, and development needs in various stages is important for successfully obtaining regulatory approval and commercialization. New nuclear reactor technology providers need to understand the potential challenges and regulatory compliances to appropriately utilize their resources. Customers of these reactor technologies need to understand and evaluate the reactor design feature to select the appropriate SMR technology, associated TRL, and required regulatory approvals to make a well-informed decision.

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