# Small modular reactors and new

# technologies in the generation capacity

# expansion: The Brazilian perspective

Gustavo Cezimbra Borges Leal

Eletronuclear S.A.

Rio de Janeiro/RJ, Brazil

Email: gcbleal@eletronuclear.gov.br

**Abstract**

The energy demand increase challenges operators to deal with multiple aspects, such as reliability, energy prices, power losses, and diversification of energy resources. In 2023, the Brazilian generation capacity rose 10.3 GW to achieve close to 200 GW of power generation under operation, and this behavior will continue. Under construction, the Angra 3 nuclear power plant will be the third unit in the Almirante Álvaro Alberto power generation complex (CNAAA), all based on pressurized water reactors. This new plant will generate up to 12000GWh/year, attending approximately 60% of Rio de Janeiro's energy consumption and increasing the nuclear participation to 3% of the national energy matrix. Following this path, small modular reactors (SMRs) emerge as a potential new technology for new plants worldwide and a new opportunity for the Brazilian energy industry. The paper analyzes the national target goals and challenges for nuclear generation, discussing the Small Modular Reactors perspective in the generation expansion studies for the Brazilian 2031 and 2050 horizons. A review of current SMR designs and plants worldwide and their aspects are presented to contextualize possible trends for Brazilian planning decisions. This work aims to debate the SMR perspective as a potential technology for new units in Brazil and new opportunities for the national nuclear sector. Furthermore, the study approaches new trends, such as the hydrogen market and nuclear fuel issues, that impact Brazil's atomic power generation industry.

## INTRODUCTION

Energy is one of the principal needs in modern society and one of the pillars of economic growth. Stimulated by the industrial strength and world population increase, energy consumption will continuously rise [1]. In 2023, the Brazilian generation capacity rose 10.3 GW to achieve close to 200 GW of power generation under operation, and this behavior will continue. Due to environmental concerns, the transition towards a low-carbon emission has become a worldwide goal, and reducing the greenhouse gas (GHG) emissions and carbon intensity of the economy have been identified as the main objectives [2].

The combination of energy demand and environmental aspects has strengthened renewable energy sources (RESs) to the detriment of conventional generation based on fossil fuels [3]. In recent years, RESs, especially wind and photovoltaic generation, received considerable investments worldwide. In Brazil, hydropower plants, which accounted for 83% of national power capacity at the beginning of the century, will reduce their relative share to 46% by 2031 [4]. However, while the considerable variability of renewable sources imposes challenges in operation, such as frequency stability, the intermittent behavior impacts the planning stage due to the non-dispatchability nature of these technologies [5, 6, 7].

Nuclear power plants significantly contribute to the battle to ensure clean energy production. Nowadays, nuclear energy is the second-largest world source of low-carbon energy, representing 10% of global energy production with controllable power output, making it a strong base power generation [2, 7]. According to the Power Reactor Information System (PRIS) from the International Atomic Energy Agency (IAEA), the world currently has 416 of 441 nuclear power reactors in operation, resulting in a total of 395.861 MWe of total net installed capacity, while 59 more reactors are under construction [8].

However, disadvantages such as long construction periods, higher CAPEX, lower flexibility, and lower social acceptance due to safety concerns have blocked the adoption of centralized nuclear power plants in several applications [7, 9 ,10]. In addition, the impact of the Three Mile (1979) and Chernobyl accidents (1986) stalled the growth of nuclear generation in the 1990s and 2000s [2]. Nevertheless, the Small Modular Reactors (SMRs), a new generation of reactor technology, have been the interest of industry and academic work in recent years with the expectation of a new era in the nuclear sector.

Commonly classified as units with power ratings from 10 to 300 MWe [7, 10, 11, 12, 13], SMR has gained the attention of the electric market worldwide, especially with the idea of multiple modules sized to medium and large power systems [12, 13]. Due to their smaller size, potential lower capital investments, faster dynamic, and modular construction aspects [5, 7, 13], SMRs have the potential to ensure a more flexible operation and emerge as possible solutions, along with RESs, to attend to energy demand in both remote and connected electrical grid [7, 14].

 At the time of writing, multiple countries such as the USA, Russia, South Korea, China, Japan, Argentina, France, and India presented new SMR systems or components currently under test or investigation [10, 13]. While India has a 200 MWe Heavy-water-cooled (HWR) reactor by the Nuclear Power Corporation of India, the other countries advanced more in Light-Water-Cooled Reactors (LWRs). Furthermore, RDIPE and Rosatom in Russia achieved advantages in lead-cooled reactors, the USA and Japan lead Sodium-cooled based solutions, and France, the USA, and China also obtained technologies in Gas-cooled reactors [13]

Several papers contributed to SMR research aspects and understanding. The authors in [5] proposed a new model to facilitate the power system studies of SMR integration, and [7] and [14], respectively, addressed the modeling of load-frequency control in islanded microgrids and hybrid energy system integration. The work in [9] discusses economic aspects and market expectations for SMR in the future of the nuclear industry and electrical energy market. Some papers focused on possible SMR integration in a future electrical matrix of countries such as Puerto Rico, the Czech Republic, South Africa, and Hungary [3, 15, 11, 12].

Brazil has two nuclear power plants of 640 MWe (Angra 1) and 1350 MWe (Angra 2). In the following years, a third plant of 1350 MWe that is currently under construction will start its operation, while Angra 1 is on the path to extend its license operation for 20 more years until 2045. All these nuclear power plants (NPPs) use pressurized water reactors, a technology that tends to dominate the Brazilian nuclear generation until 2030. Nevertheless, discussions regarding a fourth and future NPPs already started, and SMRs and other advanced modern solutions are emerging as possible solutions for Brazil in the medium- and long-term horizons. Following this path, the paper aims to discuss the SMR perspective as a potential technology for new units in Brazil and a new opportunity for the national nuclear sector.

The paper presents four sections. After this introduction, the second section briefly reviews SMR aspects, its classifications, and its current scenario in the nuclear market. Section three describes the Brazilian nuclear scenario, national fuel resources, and new technologies related to the nuclear industry. Moreover, it discusses the goals and challenges to nuclear-based power generation in Brazil and the national perspectives in both short- and long-term horizons. Finally, the last section concludes the paper and highlights the main topics.

1. SMALL MODULAR REACTORS

Traditionally, nuclear power generation gained importance with large-scale and centralized power plants for baseload generation [5, 12]. After the 1950s, nuclear power generation rose to over 400 reactors in operation at the end of the 1980s and 17.5% of global energy generation in 1996 [2, 9], but several factors impacted this expansion, as aforementioned. The SMRs’ advantages compared to large power plants, such as the faster dynamics and higher flexibility, open the field for new applications for nuclear technology, notably load-following generation, frequency regulation, ancillary services, and integration with intermittent renewable resources. Furthermore, a factory-based construction and mass production economy promises to reduce the costs and duration of new units [5, 12, 13].

According to [16], the IAEA registered over eighty SMR designs from 18 countries until 2022. There are several SMR classifications presented in literature based on distinct aspects, such as the nuclear reactor size or power, neutron spectrum (thermal and fast neutrons), and type of coolant (water-, gas-, molten-salt, and liquid-metal cooled) [10, 11]. Based on its power output, SMRs are considered the ones with electrical power up to 300 MW [3, 6, 7, 10, 11, 12], but the authors in [15] highlighted the US classification based on the thermal output of 1000 MWth. This section aims to briefly explain the principal characteristics of SMRs classified as from Generation III/III+ and IV, based majority on the work already cited in this section.

* 1. **Generation III+**

SMR based on Generation III+ reactors aimed to use technology similar to classic nuclear power plants and profit from a more established technology, adding improvements in safety features and reducing in scale to achieve the goals mentioned in the last section [12, 15]. Based on Light Water Reactors (LWR), these topologies generate electrical energy through a closed-loop system using water as the moderator/coolant and graphite as the neutron moderator, consisting majorly of the reactor vessel, control rods, reactor steam generators, and turbine generators [10, 12, 15]. Furthermore, the possibility of locating all components inside the pressure vessel (integral reactors) made PWR or BWR topology easy to adapt for SMR purposes [10].

PWR technology separates the water of the primary loop (in contact with the element fuel) from the secondary loop, where the steam flows from the steam generator to the turbine generators. In [16], IAEA registered 21 PWR-based SMR designs for land-based and 8 for water-based operations registered until 2022. The Chinese ACP100 SMR and the Argentinian CAREM SMR are currently under construction, while the NuScale VOYGR 4×/6×/12× 77-MW PWR-type SMR had its design licensed effective from 21st February 2023 [12, 16]. Moreover, Ukraine’s nuclear energy company Energoatom plans to build up to 20 Holtec SMR-160, 160-MW SMRs, with the first deployment in 2029 [12]. The two KLT-40S 2x35 MWe water-based PWRs for icebreakers started commercial operation in May 2020 [16].

Differently from the PWR systems, BWR combines the primary and secondary loops of PWR in a unique system. Therefore, the BWR topology can turn the water in contact with the fuel elements into steam, conducting this stream to the turbine generators to produce electrical energy. According to [16], four SMRs based on BWR designs are currently in detailed or conceptual designs for land-based applications: GE Hitachi BWRX-300 and three topologies (VK-300, KARAT-45, and KARAT-100) by Dollezhal Research and Development Institute of Power Engineering (NIKIET) in Russia.

* 1. **Generation IV**

Still in the research and preliminary designing stages, Generation IV reactors aimed to solve aspects such as nuclear waste, fuel cycle, alternative fuels, safety features, reliability, and overall efficiency [12, 15, 16]. At the time of writing, the Advanced Reactor Information System (ARIS) of IAEA registered 30 topologies of generation IV under the designing stage, mainly on different types of gas-cooled reactors (GCRs), liquid metal-cooled reactors (LMRs), and molten salt reactors (MSRs). Examples of Generation IV reactors in operation are the 200 MWe Shidao Bay-1 in China and 30 MW HTTR in Japan, while the 300 MW LMFR-SMR BREST-OD-300 in Russia is currently under construction [16, 17]. Amongst the six reactor technologies classified as Generation IV, three are suitable for SMR applications [12, 16].

Reactor technology using gas as the coolant is commonly divided into four stages: early GCRs, improved GCRs, HTGRs, and modular high-temperature gas-cooled reactors (mHTGRs) [10]. Amongst the 17 registered reactors designed [16], only HTGR reached the operation stage. HTGR can use distinct fuels and achieve higher temperatures than conventional PWRs, categorized according to the reactor core structure: spherical bed and prismatic reactors [10, 12]. In commercial operation, the Chinese HTR-PM consists of a 2 x 210 MWe, using a modular pebble bed reactor with Helium as coolant and graphite as a moderator [15, 16]. Also using Helium and graphite, the 30 MWt High-Temperature Engineering Test Reactor (HTTR) in Japan went through long-term high-temperature operation tests, restarting operation to new test [16].

Liquid Metal-Cooled Fast Neutrons (LMFRs) use liquid metals as coolant and operate with higher temperatures than PWR but lower than HTGRs, categorized into pool-type and loop-type [10, 12]. While the former contains the coolant inside a pool surrounding the reactor core, the latter consists of a closed loop between the reactor core, heat exchangers, and pumps [10]. The BREST-OD-300 is a pool-type 300 MWe LMFR pilot prototype for commercial reactor facilities, currently under construction, and seven more LMFR concepts are in design stages in Canada, China, France, India, Japan, and the USA [16].

First introduced in the 1950s and 1960s in the USA, the Molten Salt Reactors (MSRs) use molten salt for liquid fuel, and advanced systems use liquid fluoride or chloride salts as both the coolant and fuel carrier [10, 12]. As advantages, one can mention the enhanced safety features with operation at higher temperatures and nearly atmospheric pressure (eliminating the necessity of large containment) and flexible fuel cycle. Furthermore, the negative thermal reactivity results in an inherent load-following capability [10]. The use of Thorium as a fuel, element three times more abundant than Uranium, can reduce waste and storage times [12] and, in consequence, the operational costs and complexity.

## nuclear generation in brazil and the national perspective for the future

* 1. **Nuclear power plants in Brazil**

When writing, Brazil has two nuclear power plants for electrical energy generation named Angra I and Angra II, with 640 MWe and 1350 MWe, respectively. A third plant with 1350 MWe (Angra III) is currently under construction [18, 19, 20]. The three plants consist of pressurized water reactors (PWR), the most adopted technology in the world with 289144 MWe, and more than 73% of the plants in operation in December of 2022 [2, 17]

Capable of feeding a city with two million people, the first NPP began its commercial operation in 1985. Angra 1 was bought from Westinghouse under a turn-key contract without a transfer of knowledge between Brazilian operators and the suppliers. This led to operation setbacks in the first years that were solved during the 1990s [18]. Angra 1 has two loops, connecting the reactor core to two steam generators that produce one steam flux each to one turbine generator. Since 2019, Eletronuclear has been expending several efforts to renew the operational license of Angra 1 for twenty more years until 2045, such as the change of steam generators, weld overlay in the pressurizers, and change of the reactor vessel lid [18].

The second NPP ended its construction in 2000 and began commercial operation in 2021, with double the electrical power of the first plant. Angra 2 has four loops, connecting the reactor core to four steam generators that produce one steam flux each, generating four steam fluxes to one turbine generator. Differently from Angra 1, Angra 2 consists of a PWR technology of Siemens/KWU acquired under a National agreement between Brazil and Germany. This agreement included the transfer of knowledge to contribute to Brazil's national development and resulted in mastering practically all the stages of nuclear fuel manufacturing [19].

Still under construction in Brazil, the Angra 3 nuclear power plant will be the third national unit. Angra 3 is similar to Angra 2, both in power output and design, being acquired from Siemens/KWU by the same national agreement as Angra 2. This new plant will generate up to 12000GWh/year, attending approximately 60% of Rio de Janeiro's energy consumption and increasing the nuclear participation to 3% of the national energy matrix. The commercial operation of Angra 3 is expected to begin in 2028 [20]. Discussions regarding a fourth NPP have already started but are still in the early stages of negotiations without a defined schedule.

* 1. **The nuclear perspective in short- and long-terms in Brazil**

The Brazilian Nuclear Policy of the 5th of December 2018 established the most important guidelines for the planning and action of nuclear activities in Brazil [2]. Amongst the 19 major objectives for the nuclear area, the following must be highlighted for the electrical general area:

* Alignment with energy planning decisions regarding clean and baseload generation by nuclear power generation;
* Strengthen planning activities and safety and security demands;
* Stimulate research, development, and innovation in nuclear technology.

The new reactors of Generation III+ and SMR technology are doubtless the world’s biggest expectations of the nuclear sector for the next years. According to the Brazilian National Energy Plan [2], generation III+ reactors are at the beginning of their operational life, both in large and small reactors, and it is expected to dominate the next decades of nuclear power generation worldwide. Furthermore, the Generation IV reactors are not expected to achieve substantial importance until 2050. As depicted in the last section, only a few Generation IV reactors have begun to operate mainly in prototypes and test programs, lacking operational experience and keystone achievement toward operational readiness.

New reactors of different topologies than conventional PWR-based reactors are not expected until 2030 in Brazil. In a short-term analysis, the beginning of Angra 3 operation and license expansion for the Angra 1 power plant are the two principal achievements for the nuclear generation area, and another plant is at the beginning of the discussion [2, 4]. After 2030, new projects may continue with PWR-based systems, incorporate SMR designs, or generation IV reactors [2]. The energy demand and aspects such as flexibility, and centralized or distributed generation will impact the decision regarding new technologies, as well as the operational readiness and reliability of new reactors. However, it must be noted that Generation IV is still behind in the race toward industrialization and their availability in the nuclear market depends majorly on enhancing their technical maturity and competitiveness.

High reliability and baseload generation are advantages of nuclear technology, especially because of new intermittent power plants in Brazil, such as wind and photovoltaic. Moreover, Brazil recently went through a hydric crisis that compromised the national energy supply since almost 50% of electrical energy comes from hydropower plants. Hence, it is necessary to consider a reliable and controllable energy solution based on clean energy.

Nuclear generation attends to these challenges. Further, Brazil has the seventh-largest Uranium natural reserve in the world, in the order of 232.813 tons with less than one-third of its territory being explored for Uranium extraction [21]. Moreover, Brazil has dominated the technology for the full cycle of nuclear fuel, from extraction to the fabrication of the fuel element [2]. Nevertheless, part of the production is still occurring in foreign countries due to economic reasons and investments are necessary to strengthen the installed industrial capacity [2, 21]. Finally, one can highlight the 150 kg/day hydrogen generation plant in Angra 1 and 2 based on sodium hypochlorite (NaClO) used to clean the seawater in the PWR’s tertiary loop. The production can expand to 500 kg/day with Angra 3 operation and some technical improvements [4]

## CONCLUSION

This work aimed to present the perspective for Brazil's national nuclear sector in both short- and long-term horizons, especially the space for SMR applications in future nuclear power plants. New trends and possible markets were also highlighted, such as the hydrogen generation and expansion of the Brazilian element fuel industry. The paper studied the SMR design, features, and applications in different countries to serve as a basis for understanding their advantages and issues for the Brazilian scenario. The paper depicted the current scenario of nuclear power generation in Brazil and the national energy expansion plan for two scenarios to investigate the SMR's possible applications.

Regarding the discussion presented in the paper, one can conclude that SMRs are currently promising solutions for new NPPs in medium- and long-term horizons. Designs from both Generation III+ and Generation IV are enhancing their performance and gradually reaching milestones toward commercial operation. The increase in the number of SMR designs and the beginning of the operation of the first few SMR systems corroborates this perspective.

Nevertheless, the lack of operation experience and technical improvements that still are necessary argue against SMRs in Brazil's future until 2030. Investments in R&D to overcome constraints in developing solutions are still needed to make SMRs a reliable option for the Brazilian market. Due to SMR's advantages, such as flexibility, clean energy, and robust dispatchable energy sources, SMRs are a promising option for Brazil's energy planning. Moreover, Brazil's Uranium reserve and hydrogen generation technology are triumphs for nuclear generation, making Brazil a strong contender for energy expansion and, if SMRs are consolidated at the operation level, for SMR's future market.

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