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Original Article

Small Modular Reactors: Feasibility Analysis for Implementation in Brazil

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Abstract: Small modular reactors (SMRs) are at the forefront of new reactor designs worldwide due to their characteristics that meet the current demands from the global energy sector, combining flexibility for application with clean energy production. There are over a hundred SMR projects under development globally, utilizing different technologies. Brazil plans to use SMRs as part of its strategy to strengthen energy security and technological advancement, as foreseen in the National Energy Plan 2050 (PNE 2050). To monitor the development stage of SMR projects around the world, for which information is available in open literature, OECD/NEA created a metric based on six critical aspects influencing the implementation of these projects: licensing, location, financing, supply chain, engagement, and nuclear fuel. This paper presents the results of a bibliographic and documentary review focused on analyzing the possibilities of implementing SMRs in Brazil in order to assess the maturity level of each aspect for the implementation of this technology, adopting OECD/NEA criteria as a reference. The results revealed that, in Brazil, the six aspects evaluated show a certain degree of maturity, but there are important challenges to be faced in order to enable the implementation of SMR technology as part of the solutions to diversify the energy matrix in the coming years.

Keywords: Small Modular Reactors (SMRs), feasibility analysis, implementation in Brazil.

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Reatores Modulares de Pequeno Porte: Análise de Viabilidade para Implantação no Brasil

Resumo: Os reatores modulares de pequeno porte (SMRs) estão na vanguarda dos novos projetos de reatores no mundo devido a características que atendem às atuais demandas do setor energético mundial aliando versatilidade de aplicações com produção de energia limpa. Há mais de uma centena de projetos de SMRs em desenvolvimento no mundo, utilizando diferentes tecnologias. O Brasil planeja a utilização de SMRs como parte da estratégia de fortalecimento da segurança energética e de avanço tecnológico, conforme previsto no Plano Nacional de Energia 2050 (PNE 2050). De modo a acompanhar o estágio de desenvolvimento de projetos de SMR no mundo que apresentam informações disponíveis em literatura aberta, o NEA da OCDE criou uma métrica baseada em seis aspectos críticos que influenciam a viabilidade desses projetos: licenciamento, localização, financiamento, cadeia de suprimentos, engajamento, e combustível nuclear. Este artigo apresenta os resultados de uma revisão bibliográfica e documental focada na análise das possibilidades de implementação de SMRs no Brasil, a fim de avaliar o nível de maturidade de cada aspecto para a implementação dessa tecnologia, adotando os critérios da OCDE/NEA como referência. Os resultados revelaram que, no Brazil, os seis aspectos avaliados apresentam certo grau de maturidade, porém existem desafios importantes a serem enfrentados para viabilizar a implementação da tecnologia SMR como parte das soluções para diversificar a matriz energética nos próximos anos.

Palavras-chave: Reatores Modulares de Pequeno Porte (SMRs), viabilidade, implantação no Brasil.

1. INTRODUCTION

The growth in global demand for electricity has intensified concerns about the environmental impacts associated with the use of fossil fuels, the main emitters of greenhouse gases. The energy sector is responsible for approximately three-quarters of these emissions [1], which makes the transition to clean and sustainable sources essential. In this scenario, the diversification of the energy matrix and the use of new technologies assume a strategic role in mitigating global warming and ensuring security of supply.

In this context, nuclear energy stands out as a source of high energy density and low carbon emissions, contributing to the decarbonization and stability of electrical systems. In the member countries of the Organization for Economic Co-operation and Development (OECD), it represents the main source of non-emitting electricity and the second largest in the world, behind only hydroelectric power [2]. In addition to its relevance in electricity generation, nuclear energy has growing potential in complementary applications, such as the production of low-carbon hydrogen and synthetic fuels, reinforcing its importance in clean electrification strategies and climate finance.

The current prominence of nuclear energy stems from a technological evolution consolidated since the 20th century, marked by the discovery of nuclear fission and the construction of the first commercial reactors [3]. Currently, this source represents about 10% of the world's electricity and almost a quarter of the clean energy generated globally [4]. There are 415 reactors in operation and 62 under construction, mainly concentrated in the United States, France, China, and Russia [5], with France having the highest share of nuclear power in its electricity matrix, at approximately 70% [6].

In recent years, the nuclear sector has prioritized technological innovation, and Small Modular Reactors (SMRs) have emerged as a promising alternative to overcome the economic and operational challenges of conventional reactors. With power up to 300 MW(e), SMRs have a modular design and standardized industrial production, which reduces costs, deployment times, and operational risks. They also incorporate passive safety concepts and a reduced radioactive inventory, which decrease the potential for accidents and facilitate waste management. Modularity allows for scalability, lower initial investment, and installation in remote locations, as well as enabling factory testing that increases system reliability. In some projects, underground or submerged installation ensures greater protection against natural hazards and external actions [7].

The concept of SMRs originates from compact reactors developed in the 1950s for naval propulsion and has since evolved into civilian applications in electricity generation, desalination, and hydrogen production. There are currently 127 SMR projects under development in the world [8], encompassing different technologies, in addition to PWR. Among the examples in operation, the KLT-40S (Russia) and the HTR-PM (China) stand out [9].

For Brazil, the adoption of SMRs represents a strategic opportunity to strengthen energy security and technological advancement, with the potential to contribute significantly to the reduction of carbon emissions and the diversification of the electricity matrix. The technology is supported by the National Energy Plan 2050 (PNE 2050), which recognizes it as disruptive and foresees its commercial availability in the country by the 2030s [10].

However, the effective implementation of SMRs requires an understanding of the particularities of the Brazilian context, considering technical, economic, institutional, and regulatory aspects. In order to support this kind of evaluation around the world, the OECD Nuclear Energy Agency (NEA) identifies six critical aspects that influence the viability of SMR projects: licensing, location, financing, supply chain, engagement, and nuclear fuel [8]. An integrated analysis of these factors is essential to guide public policies and investment decisions in the sector.

In this sense, this paper evaluates the feasibility of implementing SMRs in Brazil by analyzing the maturity level of the six critical aspects defined by the OECD/NEA in the national context. The results allow the identification of gaps, challenges, and potentials related to the adoption of SMRs in Brazil, offering initial support for the formulation of public policies and for decision-making by public and private agents in the nuclear sector.

2. METHODOLOGY

This study is based on a literature and document review focused on analyzing the feasibility of implementing SMRs in Brazil, with a focus on the national context. To guide the selection of the aspects analyzed and to structure the assessment of the degree of maturity associated with the implementation of this technology, the SMR Dashboard developed by the OECD/NEA was adopted as a reference [8], used as a conceptual and organizational instrument.

The SMR Dashboard [8] establishes a set of aspects associated with the implementation of SMRs, which were used in this study as analytical axes. The aspects considered were licensing, location, financing, supply chain, engagement, and nuclear fuel, selected for their direct relevance to the feasibility of SMR projects.

The literature and document review covered academic publications, technical reports, institutional and regulatory documents related to the Brazilian nuclear sector. The selection of sources prioritized official materials and specialized literature capable of characterizing the stage of development of the country in each one of the aspects analyzed.

The analysis of the sources was conducted to classify the degree of maturity of each level using an ordinal scale composed of five levels: incipient or non-existent, initial or fragile, intermediate or consolidating, advanced with gaps, and fully consolidated. Based on this analysis, inspired by the progression structure applied in the SMR Dashboard [8], gauge indicators and a radar chart were created, in order to represent the stages of maturity in the national context.

3. Results and Discussion

The six evaluated aspects are presented and discussed below, based on these results the degree of maturity of each aspect was defined and represented as diagram and chart according to SMR Dashboard [8] guidelines.

3.1. Licensing

The Brazilian regulatory context for nuclear activities presents a relevant level of maturity, supported by a consolidated normative base and recent institutional advances. The Federal Constitution assigns to the Union the competence to regulate and supervise nuclear activities, establishing a centralized arrangement for licensing and nuclear safety in the country [11].

In this context, the creation of the National Nuclear Safety Authority (ANSN), established by Law No. 14,222/2021, represented a milestone in the institutional redesign of the Brazilian nuclear sector, by promoting the separation between the functions of promotion and regulation and strengthening regulatory governance [12].

From a technical and regulatory standpoint, the Brazilian nuclear licensing process encompasses all stages of the facilities' life cycle, from site approval to operation, including life extension, and decommissioning.

However, the literature reviewed indicates challenges associated with adapting this framework to the specificities of SMRs. Modularization imposes additional requirements on licensing processes, including the need for inspections, certifications, and tests in a factory environment, as well as issues related to the validity of certifications after the transport and installation of the modules, which can increase regulatory complexity and the perception of risk until the granting of the final operating license [13].

Overall, the results indicate that licensing in Brazil is at an intermediate to advanced stage of maturity. The country has a solid and evolving regulatory framework, with recent institutional advances, but still faces gaps related to the temporal predictability of processes, regulatory modernization, and adaptation to the characteristics of modular technology. Thus, licensing is a relatively well-developed aspect, although it depends on further adjustments to offer greater regulatory efficiency and legal certainty to the implementation of modular technology in the national context.

3.2. Location

The location of nuclear facilities is a strategic aspect for the expansion of nuclear power generation in Brazil, according to guidelines established in long-term energy planning instruments. The National Energy Plan 2050 foresees a significant expansion of the country's installed nuclear capacity, which implies the need to identify, qualify and validate new sites suitable for the implementation of nuclear power plants, in accordance with criteria of safety, environmental viability and social acceptability [14].

The Brazilian regulatory framework establishes general guidelines for the selection of nuclear sites, based on safety criteria. However, the literature indicates that these criteria are predominantly qualitative and empirical, reflecting the limited experience accumulated in defining more robust quantitative parameters for choosing locations for the installation of power reactors.

The evaluation of nuclear sites in Brazil involves the integrated analysis of reactor design characteristics and specific site conditions. Technical factors are considered, such as power and radioactive inventory, as well as geographical, geological, hydrological, meteorological and demographic characteristics, in addition to the availability of infrastructure and adequate access routes for emergency response. This set of variables aims to ensure that the probability of accidents with significant release of radioactive material is extremely low and that any consequences are adequately mitigated [15].

The process of selecting and qualifying nuclear sites in Brazil tends to be long and complex. Studies indicate that the choice and validation of a site can take between six and ten years, encompassing successive phases of preliminary analysis, pre-design and design, with progressively more detailed investigations and the involvement of different technical specialties [16]. This characteristic reinforces the need for long-term planning and institutional stability to enable new nuclear projects.

In recent years, institutional initiatives have sought to improve the process of selecting nuclear sites in Brazil. Studies conducted within Eletronuclear, with the support of national and international institutions, have identified promising areas in different regions of the country, based on methodologies adapted from consolidated international references [17]. Initially, areas in Northeast and Southeast of Brazil were evaluated, and subsequently, the research expanded to identify 40 candidate areas throughout the national territory, with two of them, in particular, highlighted as the most promising: the Itacuruba site in Pernambuco and the São Romão site in Minas Gerais [17]. In the specific context of SMRs, the literature indicates that characteristics such as lower unit power, reduced deployment area, and the incorporation of passive safety systems increase locational flexibility compared to conventional nuclear power plants. Studies point to the feasibility of deploying these reactors in remote regions or near areas with significant energy demand, as well as in non-electrical applications, provided that adequate safety, infrastructure, and public acceptance requirements are met [18].

In general, the results indicate that the location aspect in Brazil is at an intermediate stage of maturity. The country has normative guidelines and accumulated experience in site selection processes, in addition to recent initiatives aimed at methodological improvement. However, challenges related to the duration of the processes, the dependence on empirical evaluations, and the more systematic integration of socio-environmental and strategic criteria persist. In this scenario, SMRs represent a relevant opportunity for the territorial diversification of nuclear generation.

3.3. Financing

The financing of nuclear projects in Brazil is characterized by an institutional structure that is strongly centralized in the State, due to the strategic and sensitive nature of the sector. Historically, the main national nuclear projects have been made possible through public resources, with emphasis on budgetary allocations and government support instruments. This arrangement reflects the high capital intensity, the long maturation periods and the risks associated with these projects, which have traditionally limited the participation of private sources of financing.

In the field of Research, Development and Innovation, Brazil has a diverse set of public support instruments, which includes non-reimbursable mechanisms, reimbursable financing and tax incentives. These instruments are operated by institutions such as Funding Authority for Studies and Projects (FINEP), Brazilian Development Bank (BNDES), National Council for Scientific and Technological Development (CNPq), in addition to the National Development, Scientific and Technological Funding (FNDCT) which plays a central role in financing strategic and structuring projects of national interest [19].

Nuclear projects face significant financial challenges due to the high cost of capital, technical complexity, long construction times, and the risk of delays and budget overruns, factors that increase the perception of risk by investors and financial institutions [20]. The construction phase concentrates most of these risks, while the operational stage tends to present greater revenue stability, favoring debt refinancing under more favorable conditions.

In this context, risk mitigation plays a central role in the financial viability of nuclear projects. Strategies such as government support, credit guarantees, long-term power purchase agreements, asset-based regulatory models, and diversification of funding sources are identified as fundamental to reducing the cost of capital and increasing the attractiveness of projects. International cooperation also emerges as a relevant vector, enabling access to external financing, technology transfer, and institutional strengthening [21].

Among the alternatives to enable SMR projects in Brazil are Public-Private Partnerships (PPPs), which would allow for the sharing of costs and risks between the government and private investors. Other options include government support through subsidies and tax incentives, attracting institutional investors and venture capital interested in sustainable technologies, adopting models based on regulated tariffs to guarantee returns for investors during the construction phase, and entering into long-term power purchase agreements with distributors or large consumers to ensure revenue stability [21].

In the specific case of SMRs, the literature indicates that characteristics such as modularity, standardization, and serial production can contribute to reducing deadlines and uncertainties, especially in units subsequent to the First-of-A-Kind (FOAK). These factors tend to improve the risk profile over time, increasing the economic competitiveness of SMRs in the medium and long term and reinforcing their potential as a complementary alternative in the expansion of nuclear generation [22].

In general, the results indicate that Brazil has diversified and evolving financial instruments, with recent advances in the field of sustainable finance and in the structuring of financing models for infrastructure. However, relevant barriers associated with the risks of the construction phase, the high capital intensity, and institutional and constitutional restrictions persist, limiting the attractiveness of large-scale private investment in the nuclear sector.

3.4. Supply Chain

The nuclear supply chain is highly specialized and differs substantially from conventional industrial chains, as it involves technical and regulatory processes distributed throughout the entire life cycle of the facilities, from initial stages to decommissioning. It is also a globalized chain, with suppliers distributed internationally, which increases the complexity of coordination, control, and resilience of the supply links [23]. In new projects, decisions made in the initial phases impact the entire lifespan of the facility, while the operating phase demands replacement items and maintenance services, requiring strategic and integrated action from the supply areas.

The criticality of the goods and services used in the nuclear sector imposes rigorous requirements for quality, traceability, and reliability at all stages of the chain. Quality assurance and control systems are identified as pillars to ensure safe performance and operational efficiency, especially in a sector where failures can compromise safety and institutional credibility. Furthermore, the geographical dispersion of suppliers and technological evolution increase the challenges of supervision and compliance, reinforcing the need for systematic monitoring, prevention of counterfeit items and management of risks associated with obsolescence and digitalization [24].

On the regulatory level, international guidelines emphasize that, even when activities are outsourced, responsibility for safety remains with the operating organization, requiring qualification, rigorous evaluation and supervision of suppliers and the adoption of robust procurement, quality and performance control practices [25].

In the Brazilian case, a supply chain structure with relevant institutional and industrial hubs is observed, with territorial concentration that favors logistical and institutional articulation. The presence of installed infrastructure and strategic actors linked to fuel generation and cycle sustains national capabilities in stages such as mining, enrichment, and manufacturing of fuel assemblies, albeit with limitations in certain critical links. In particular, the absence of national industrial dominance in the conversion stage to UF_6 maintains external dependence, despite the existence of pilot-scale technology, which represents a significant vulnerability in the autonomy of the fuel cycle [26].

It is important to highlight that the Brazilian nuclear sector is integrated into the Defense Industrial Base (DIB), a set of public and private organizations responsible for the research, development, production and maintenance of goods and services of strategic interest. This contributes to reduce external dependencies and strengthen industrial and technological infrastructure for application in other important areas such as oil and gas.

In the construction and equipment supply stage, the country has expertise in engineering, assembly and heavy boiler making, but remains dependent on large forgings and industrial capabilities available only in a few countries, configuring a critical bottleneck, aggravated by the global scarcity of these items in the face of increased demand for new reactors. On the other hand, conventional systems and auxiliary equipment allow for greater participation of national suppliers, provided that rigorous qualification and quality control requirements are met, which expands opportunities for the insertion of Brazilian companies along different levels of the chain [26]. The Brazilian regulatory framework for the supply chain presents specific instruments for qualification and certification, with emphasis on quality assurance and traceability, qualification of technical personnel and requirements applicable to the acquisition and manufacture of fuel assemblies. This regulatory framework contributes to standardizing practices and ensuring regulatory compliance, provided that it is applied consistently across the different levels and sub-suppliers of the chain [27], [28], [29].

In the context of SMR, studies indicate that the supply chain remains a central component for competitiveness, highlighting the need for strategic partnerships for key components and for the gradual transition to more consolidated models as modules are delivered and production becomes more serialized. The literature also points out that the adoption of SMR may require adjustments to the fuel cycle, with potential impacts associated with specific supply requirements, in addition to the importance of cooperation in research and development to ensure qualified labor and technical infrastructure [30].

In general, the results indicate that the Brazilian supply chain has relevant installed capacities, but coexists with structural vulnerabilities in critical links and in the continuity of investments. External dependence on conversion to UF_6, national limitations in the production of large forgings, the fragility of the specialized services ecosystem, and the challenges associated with human resources and demand predictability are central points for the maturity of this aspect. Thus, although there are consolidated institutional and regulatory bases, strengthening the supply chain requires further progress to reduce dependencies and increase resilience to face the future sector expansion.

3.5. Engagement

Stakeholder engagement is a central element for the viability and legitimacy of nuclear programs, given that these undertakings involve long-term decisions, significant investments, and high levels of social scrutiny. The literature highlights that the absence of structured dialogue can amplify resistance, compromise institutional trust, and affect the continuity of projects, especially in contexts where there is information asymmetry and low public familiarity with peaceful applications of nuclear technology [31].

From a conceptual point of view, engagement is treated as a dynamic and adaptable process, which requires careful identification of statutory and non-statutory groups, as well as the adoption of strategies responsive to the sociocultural and institutional characteristics of each country. Although consensus is not guaranteed, transparency in the decision-making process, predictability of dialogue channels, and clear communication about risks and benefits are identified as fundamental conditions for strengthening public trust and sustaining a sociopolitical atmosphere favorable to nuclear development [31].

In the Brazilian case, there is a history of international engagement associated with credibility and non-proliferation, marked by regional and multilateral commitments that reinforce the peaceful use of nuclear energy. Instruments such as the Treaty of Tlatelolco, the creation of Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) and the formalization of the Quadripartite Agreement with the International Atomic Energy Agency (IAEA) constitute relevant institutional milestones for building international trust and for the country's insertion into safeguards and verification regimes [32].

At the national level, there are formal mechanisms for participation and transparency linked to regulatory and decision-making processes. In the nuclear field, ANSN has instruments such as public consultations and institutional channels aimed at social participation, such as ombudsman and access to information, with the potential to increase the predictability and legitimacy of the regulatory process. In addition, technical forums, inter-institutional commissions and debates in the National Congress make up complementary instances, with the capacity to bring together experts and social actors and to increase transparency in the formulation of policies related to nuclear energy [33].

Despite the existence of these instruments, studies indicate weaknesses in building social trust and in the effectiveness of public engagement. Evidence points to widespread public ignorance about the sector, with recurring association of nuclear energy with risks, accidents and weapons, as well as a perception of institutional communication that is not very dialogical and predominantly unidirectional. These factors suggest limitations in the public communication strategy and reinforce the need for accessible language, audience segmentation, and strengthening of sources considered reliable, such as universities and research institutes [34].

Overall, the results suggest that Brazil possesses formal instruments for engagement and a relevant trajectory of international cooperation and non-proliferation commitments, but faces consistent challenges in the domestic dimension, especially regarding public communication, information asymmetry, and social credibility in local contexts. Thus, although an institutional basis for participation exists, advancing maturity depends on strengthening more responsive and continuous engagement strategies capable of sustaining social legitimacy in future projects, including in the scenario of possible SMR implementation.

3.6. Nuclear Fuel

The results indicate an arrangement of competencies distributed throughout the cycle in Brazil, with consolidated stages and structural gaps. In the initial stage, mining and beneficiation constitute a strategic link, with production conducted by INB in Caetité/BA and potential for expansion associated with projects such as Santa Quitéria/CE, still conditioned by technical-regulatory variables and environmental licensing. This scenario reveals that, despite the relevance of national reserves and the still underexplored geological potential, domestic production has presented scale fluctuations and capacity limitations, maintaining complementary dependencies and restricting greater insertion of the country in the mineral market [35].

The main structural vulnerability of the Brazilian cycle remains concentrated in the conversion of concentrate into UF_6, a critical step to enable enrichment by ultracentrifugation, but which is still carried out abroad, which increases exposure to supply risks and logistical and contractual dependencies.

In contrast, the enrichment stage shows signs of incremental evolution and a consolidation trajectory. Ultracentrifugation technology, developed nationally and implemented in a modular way, is a strategic asset of the country. However, the results reinforce that capacity expansion remains gradual and that part of the demand continues to be met by imports, with direct implications for autonomy and supply predictability.

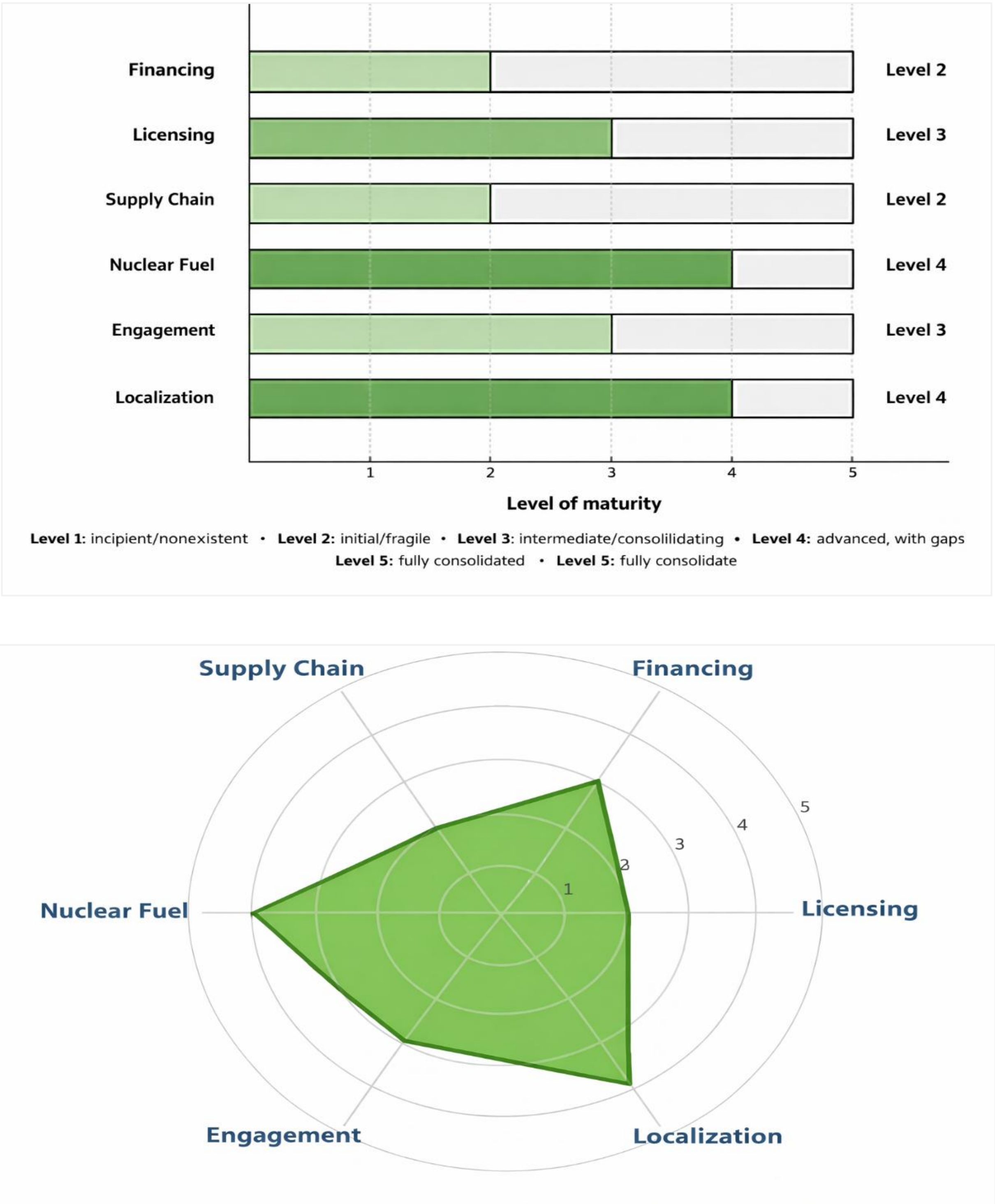
In the later stages: conversion to UO_2, pellet manufacturing, and fuel assembling, a more consolidated industrial infrastructure is observed, with installed capacity and quality control routines that support the refueling of Angra 1 and Angra 2 and constitute a basis for future expansion, including Angra 3 and associated projects [36].

Recent studies and debates reinforce that the central challenge is not limited to technological mastery, but involves conditions of scale, financing, and continuity of investments to consolidate vertical integration. Evidence highlights budgetary constraints and limitations of scale as factors that delay the expansion of enrichment and restrict the evolution of the sector, while associative models and partnerships appear as alternatives to expand capacity and diversify revenues, including export initiatives and technical cooperation [37].

In addition, recent sectoral discussions have emphasized the risk of future imbalance between uranium supply and demand and the need to move the country towards higher value-added stages, such as conversion and enrichment on an industrial scale, also highlighting the importance of an attractive and stable regulatory framework for long-term investments [38].

3.7. Maturity Level in Brazil

Figure 1: Gauge indicators diagram and radar chart representing the maturity level of the six critical aspects defined by OECD/NEA in the national context.



4. CONCLUSIONS

The scenario outlined by this study shows that some aspects considered by the OECD/NEA present gaps and challenges that need to be addressed in Brazil, aiming the implementation of SMR projects in the near future.

Regarding licensing, Brazil has a consolidated regulatory framework, but it needs to be adapted to streamline licensing processes associated with new reactor projects, such as SMRs. Also regarding location, Brazil has solid normative guidelines; however, it is necessary to address problems related to the long time spent on processes and socio-environmental integration.

Financing, considering the high capital intensity during the construction phase, should be considered a special challenge, specifically due to the lack of attractiveness and restrictions on private investment in the nuclear sector. Structural vulnerabilities in critical links and the discontinuity of investments emerged as the main challenges associated with the supply chain aspect in Brazil.

Regarding engagement, Brazil has formal instruments and relevant international cooperation, but needs to improve domestic mechanisms related to public communication to broaden knowledge and social credibility associated with nuclear applications. Finally, the main challenge related to nuclear fuel is to be fully independent in carrying out the conversion and enrichment stages of the fuel cycle on an industrial scale, as well as adapting installed fuel production capacities to new types of nuclear fuels.

These results can be used as initial support for the formulation of public policies and for decision-making by public and private agents in the nuclear sector, aiming the implementation of SMRs in Brazil.

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CONTRIBUTORSHIP

Conceptualization: LSV, CG

Investigation: LSV, CG

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

Interview transcripts and qualitative data are not publicly available due to confidentiality commitments made to research participants. Aggregated data supporting the findings are available from the corresponding author upon reasonable request and subject to participant privacy protections.

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