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Preliminary Risk Analysis for the Installation of Small Modular Reactors in Energy-Deficient Regions of Brazil

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Abstract: This paper aims to review the feasibility of implementing PWR-type Small Modular Reactors (SMRs) in Brazil, utilizing the 5W2H methodology for a preliminary risk assessment. SMRs are seen as a promising solution to meet the country's growing electricity demand and diversify its energy matrix, particularly in underserved regions. With projections extending to 2050, the construction of these reactors offers significant benefits, leveraging modularization techniques to accelerate deployment and reduce costs. Selecting optimal locations—such as areas near the São Francisco River—and fostering collaboration between government and private entities are crucial for the project's success. While this analysis is preliminary, the findings suggest that SMR adoption in Brazil presents a strategic opportunity to enhance energy sustainability, reduce greenhouse gas emissions, and ensure a secure and efficient energy future for the country's most disadvantaged regions.

Keywords: SMR, 5W2H, SMR's costs, Risk analysis.

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Análise preliminar de riscos na instalação de Small Modular Reactors nas regiões carentes de energia no Brasil

Resumo: Este trabalho tem como objetivo realizar uma revisão bibliográfica sobre a viabilidade da implantação de reatores nucleares modulares de pequeno porte (SMRs) do tipo PWR no Brasil, utilizando a metodologia 5W2H para uma análise preliminar de risco. A construção de SMRs é vista como uma solução promissora para atender à crescente demanda por energia elétrica e diversificar a matriz energética do país, especialmente em regiões carentes. Com planejamento até 2050, esses reatores podem trazer benefícios significativos, aproveitando técnicas de modularização que aceleram a implantação e reduzem custos. A escolha de locais estratégicos, como áreas próximas ao Rio São Francisco, aliada à colaboração entre entidades governamentais e privadas, é fundamental para o sucesso do projeto. Embora esta análise seja preliminar, os resultados indicam que a adoção de SMRs no Brasil representa uma oportunidade estratégica para impulsionar a sustentabilidade energética, reduzir as emissões de gases de efeito estufa e garantir um futuro energético seguro e eficiente para as regiões mais necessitadas do país.

Palavras-chave: SMR, 5W2H, Custos de um SMR, Análise de risco.

1. INTRODUCTION

Brazil's energy demand has significantly increased, with projections indicating a rise of over 200% by 2050. The energy mix is expected to shift, with a growing role for natural gas, biomass, wind, and nuclear energy, while oil and hydroelectric power decrease. Population growth, with an additional 21 million people by 2050, is a key factor.

Energy planning in Brazil was revitalized due to rising fossil fuel prices, climate change, and hydroelectric limitations. Although Brazil relies heavily on renewable energy, concerns about water resource seasonality have increased interest in alternative sources like wind, solar, biomass, and nuclear power. The National Energy Plan 2050 and Sustainable Electric Agenda (2020) emphasize the need for diversification to meet future energy demands and reduce dependency on hydroelectricity [1] [2]. CO2 emissions are a growing concern, requiring consistent reductions of 1.4 GtCO2 annually to achieve net-zero by 2050. Nuclear energy is seen as a stable and clean solution, contributing to energy diversification. Despite its declining global share from 10.4% in 2018, nuclear power remains essential for a sustainable energy transition, as highlighted by the IAEA (2022) [3] [4].

Small Modular Reactors (SMRs) are emerging as a safer, more efficient, and cost-effective alternative to large reactors. SMRs feature passive safety systems, greater automation, and shorter construction times, offering power capacities from 10 to 625 MW(e) compared to over 1,200 MW(e) for traditional reactors [5]. However, the introduction of Small Modular Reactors (SMRs) in Brazil represents an opportunity to diversify the energy matrix, ensuring greater security and sustainability. With advantages such as lower initial costs, flexibility, and faster construction, SMRs are ideal for meeting the country's energy demand. For their implementation, it is essential to adopt adaptable commercialization models and establish a robust regulatory framework, in addition to promoting investments and public-private partnerships. Eletronuclear will play a key role in supervising and operating these plants. However, the success of this transition will depend on strategic planning that balances efficiency, economic feasibility, and public acceptance [6].

The preliminary risk analysis is carried out in this work, because the risks involved in a nuclear installation are much more complex [7].

2. MATERIALS AND METHODS

Based on a bibliographic review, some methodologies used in risk analysis were found both in the industry and in the area of nuclear reactors. However, to carry out this study, the 5W2H methodology described will be used, divided into seven questions derived from the method.

The 5W2H methodology is a management and planning tool widely used in the business world to help define and execute projects, tasks, or action plans. This methodology gets its name from the fact that it asks several questions, serving as an administrative checklist of activities, responsibilities, and deadlines to make objectives efficient and clear for a group or project. This technique also helps clarify important aspects for all participants, such as where it will be done, when it will be done, how it will be done, why it will be done, who will do it, what will be done, and how much the project will cost [8][9]. The name "5W2H" is an acronym that represents seven questions in English, each starting with a specific letter. Here is what each letter represents: (a) What?; (b) Why?; (c) When?; (d) Where?; (e) Who?; (f) How?; and (g) How much?.

The 5W2H methodology answers essential questions to avoid doubts in the execution of the project, contributing to strategic, tactical, and operational planning. After collecting the responses, it is essential to prioritize the risks based on their severity and probability of occurrence, allowing the implementation of preventive or mitigating measures [10]. The implementation of this methodology in nuclear facilities does not require extensive knowledge of the plant in operation, making it suitable for preliminary risk analyses in SMR reactors in energy-deficient regions of Brazil. These questions involve a specific methodology, which will be answered in the results chapter.

What? - A preliminary risk analysis will be conducted for the construction of SMRs-type nuclear reactors in Brazil, utilizing bibliographic research on the construction of small modular reactors to promote growth in underprivileged regions of the country and address their energy demand. Information from reports by both EPE and IAEA will be used, as presented in item 3 [1] [4].

Why? - The incorporation of SMRs can bring several advantages to Brazil, such as diversification of the energy matrix, reduction of dependence on fossil fuels, non-dependence on seasonality for energy generation, greater energy security, flexibility in construction and operation, lower risk of nuclear accidents and reduction of radioactive waste generation. The bibliography used in this work includes reports from EPE and references [1][11], highlighting the benefits of SMRs compared to large reactors.

When? - The study involves a literature review of SMR construction schedules, considering qualitative and quantitative studies. The federal government's strategic planning, through EPE studies such as PNE 2030 and PNE 2050, will be evaluated. A literature survey of data conducted with construction professionals, studies on temporal factors and comparisons with traditional construction methods will also be carried out to provide a more realistic view of construction schedules [1] [12].

Where? - The choice of locations for SMR construction will be based on a detailed assessment using the EPRI Siting Guide model and the Fuzzy methodology, drawing on detailed reports on physical characteristics, nearby populations, access roads, and water bodies, as produced according to BARROS et al. (2012). Underprivileged regions, based on the Human Development Index (HDI) provided by the Brazilian Institute of Geography and Statistics (IBGE), were considered in these reports [13][14].

Who? - The construction of SMRs in Brazil involves the federal government, Eletronuclear, and Nuclebrás Equipamentos Pesados S/A (NUCLEP). The project may be acquired by one of the international companies developing SMRs. Responsibility is shared between the state, the nuclear industry, and the private sector, with detailed planning considering technical, financial, environmental, and regulatory feasibility, with the installation and operation license being issued by Brazil's licensing body, the National Nuclear Energy Commission (CNEN). The PNE 2050 report highlights the importance of a well-managed regulatory framework to ensure compliance with safety standards and licensing procedures [15][16].

How? - The construction methodology will be based on the PNE 2050, developed by EPE, addressing issues of safety, public perception, regulatory structure, and financing. With the selection of the site, financing will be discussed to make the construction of the SMR viable [1].

How Much? - To estimate the cost of energy generation in nuclear plants, the calculation methodology of CARVALHO and SAUER (2011) [17] was used, with adjustments in values according to the amount of energy generated and the construction time and useful life. Below are the main cost components involved. In 2009, the value of Angra 3 was US$ 4,660,000,000, with dollar correction for 2024, according to the Bureau of Labor Statistics inflation calculator, around 46%, resulting in US$ 6,803,600,000 [18]. According to CARVALHO and SAUER (2011) [17], utility expenses are calculated as a percentage of the reactor's total cost (Dc - currency), that is, 8% of the Construction Value (C1 - currency), as per Equation (1):

$$\boldsymbol{D_C = 0,08 * C1} \quad (1)$$

The Total Reactor Cost (C3) is obtained by summing the Direct Costs (C2) and the interest charged during construction, as per Equations (2) and (3):

$$C2 = D_C + C1 \tag{2}$$

$$C3 = 0,7 * C2(1 + TLP)^n + 0,3 * C2(1 + Equity)^n \tag{3}$$

Where:

- TLP is the Long-Term Rate (10% per year) [19];
- Equity is the return rate (10% per year);
- "n" is the number of years of construction (assumed to be 6 years).

The Capital Recovery Factor (FRC) uses the internal rate of return (i) of 10% per year, given by Equation (4):

$$FRC = \frac{i(1+i)^t}{(1+i)^t - 1} = \frac{0,1(1+0,1)^{50}}{(1+0,1)^{50} - 1} \tag{4}$$

Where: t is the reactor's useful life (assumed to be 50 years).

With the obtained FRC, the Capital Recovery Annuity (ARC) is calculated using Equation (5):

$$ARC = FRC * C3 \tag{5}$$

Next, the Operational Costs (CO), including insurance, maintenance, and personnel and administrative costs are obtained according to Equations (6), (7), and (8) given below, where: Insurance is 10% of the ARC, Equation (6):

$$Insurance = 0,1 * ARC \tag{6}$$

Maintenance is 3% of the plant cost (C1), Equation (7):

$$Maintenance = 0,03 * C1 \tag{7}$$

Personnel and Administrative Costs (CE - currency): 0.3% of the plant cost (C3), Equation (8):

$$CE = 0,003 * C3 \tag{8}$$

The Total Annual Operation Cost (CTO - currency) is the sum of ARC, insurance, maintenance, and personnel and administrative costs, as shown in Equation (9):

$$CTO_{Annual} = ARC + Insurance + Maintenance + CE \tag{9}$$

The Annual Cost per Energy Produced (AC - currency/MWyear) is calculated relative to the energy generated by the reactor, given by Equation (10):

$$CA = \frac{CTO_{Annual}}{Energy\ generated\ in\ one\ year\ by\ the\ reactor} \tag{10}$$

The specific capital cost for SMRs is estimated based on the economy of scale curve and the reactor's nominal power, using appropriate scale factors. Additionally, the fact that reactors are among the first or the nth constructed influences the total value. The first of their kind to be built are called First Of A Kind (FOAK) and generally have higher costs due to uncertainties and lack of experience. With the experience gained in subsequent constructions, these reactors, after a certain learning level, are defined as Nth Of A Kind (NOAK). Building NOAK reactors can generate a cost reduction of 15% to 40% compared to FOAK reactors. Constructing a FOAK can take 5 to 6 years, while subsequent reactors can be built in as little as 3 years, mainly for SMRs of the same type [20]. The learning curve also leads to a reduction in production costs, which decreases as experience increases, with a learning rate that can vary from 2% to 6%, depending on technological maturity. All these factors will be considered in the final cost of nuclear reactors.

According to CARELLI et al. (2010), the cost of an SMR can be estimated based on calculations for large reactors [21].Therefore, comparisons between the costs of large reactors and SMRs help provide a closer estimate of construction and operation costs. Equations (11) and (12) are used to size the costs between large reactors with power up to 1,300 MW(e) and SMRs with power less than 600 MW(e). These equations are applied to calculate the cost of PWR-type SMRs relative to large PWR-type reactors, considering the average scale factor (η), adjusted according to the reactor's nominal power.

$$\frac{Cost\ (P_{SMR})}{P_{SMR}} = \frac{Cost\ (P_{LR})}{P_{LR}} \left(\frac{P_{SMR}}{P_{LR}}\right)^{\eta-1} \qquad (11)$$

$$Cost\ (P_{SMR}) = Cost\ (P_{LR}) \left(\frac{P_{SMR}}{P_{LR}}\right)^{\eta} \qquad (12)$$

Where:

Cost (PSMR) - Cost of an SMR-type reactor (PWR) in dollars (US$);

Cost (PLR) - Cost of a large-scale reactor (PWR) in dollars (US$);

PSMR - Power of an SMR-type reactor (PWR) in MW(e);

PLR - Power of a large-scale reactor (PWR) in MW(e);

η - Average scale factor.

To calculate an SMR, the average scale factor increases with the reactor's nominal power, as discussed by BOLDON and SABHARWALL (2014) [20]. For reactors smaller than 35 MW(e), the scale factor is approximately 0.6, while for reactors up to 600 MW(e), the factor is adjusted according to Equation (13). For larger reactors, the scale factor remains constant at 1.

$$\eta = 4x10^{-10}(P_R)^3 - 10^{-6}(P_R)^2 + 0{,}0012(P_R) + 0{,}581 \qquad (13)$$

Using the previous formulas for calculating annual values and the construction costs of a nuclear reactor, a program was developed to obtain these values in a consolidated and virtual manner. The calculation program was developed in C# (C-Sharp) and Windows Forms, with the collaboration of student Orlando Si Kae Fang. The program was named Economic Feasibility Calculation Program for SMRs (PROVES) for PWRs is presented in item 3.

3. RESULTS AND DISCUSSIONS

The 5W2H technique is a systematic and organized approach to identifying and evaluating potential risks and implementing risk management strategies in a project or process. In this study, questions were asked concerning the preliminary analysis of the risks associated with the implementation and operation of an SMR in the most energy-deficient regions of Brazil. Starting with the first question, What?

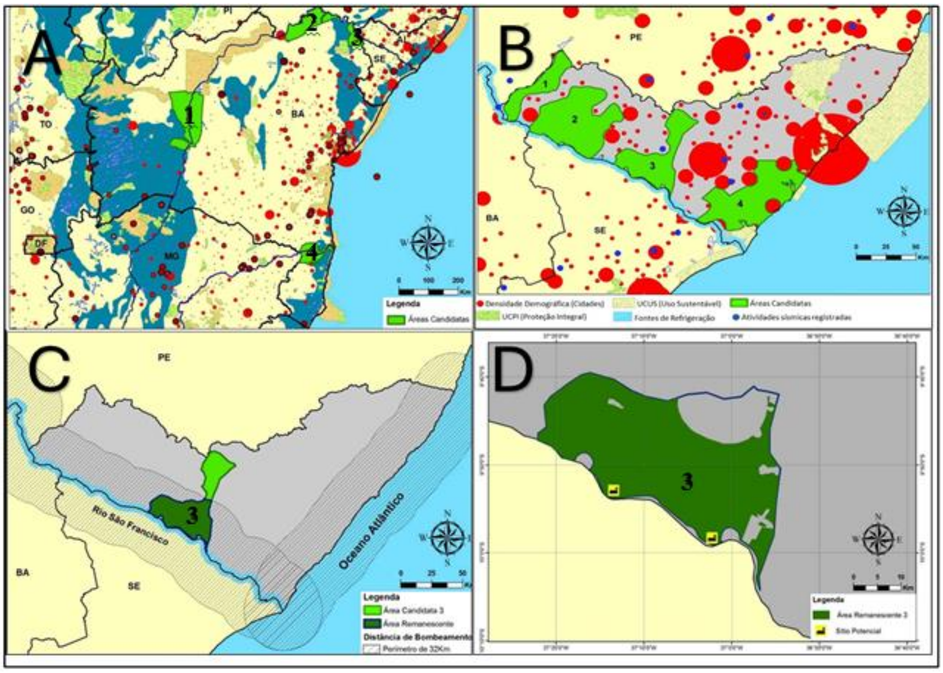
What? - As discussed previously, this research aims at a preliminary analysis for the construction of a SMR in Brazil. This initiative seeks to meet the growing energy demand, especially in underserved regions of the country. It is not possible to produce a report on the construction process, as it involves detailed planning, high safety standards, and nuclear waste management, as highlighted by CNEN (2022) [16]. Furthermore, the research incorporates an integrated vision to address the energy and drinking water supply challenges of SMRs, aligning with the diversification of the energy matrix and reducing greenhouse gas emissions [1]. SMRs are identified as a promising solution to provide firm energy in underserved regions of the country [5]. The research also proposes investments in energy efficiency in several sectors to reduce the consumption of non-renewable energy sources.

Why? - Brazil faces challenges like social inequality, poverty, and inadequate infrastructure. Sustainable economic growth driven by clean, renewable energy is key to addressing these issues. The PNE 2050 outlines goals to boost the share of renewable and nuclear energy in the energy matrix [1]. Nuclear energy, being clean and emission-free, is crucial for underprivileged areas. Small Modular Reactors (SMRs) provide construction flexibility, cost reduction, lower socio-environmental impacts, and advanced safety systems to minimize nuclear risks. SMRs efficiently meet energy demands of small communities and businesses, supporting Brazil's sustainable development [21][22].

When? – According to the PNE 2050 report by EPE (2020), Brazil plans to start constructing a nuclear reactor in 2030, with an expected inauguration in 2038, depending on funding and government priorities [1]. Modular construction can reduce construction time by up to 40% compared to traditional methods [23][24]. For instance, the Delta House Project saved 2-3 years using modular techniques [25][26]. Estimates for a Small Modular Reactor (SMR), such as a PWR, suggest a three-year pre-project phase and a 5-6 year construction period, with subsequent projects optimized for faster completion [27]. NuScale in the USA estimates five years per plant, two years faster than conventional reactors [27]. In Brazil, SMR construction faces political and financial uncertainties. However, a tentative schedule includes a one-year contracting phase, one year for foundation work, 36 months for reactor assembly, six months of testing, and one year for licensing and grid connection [28]. If conditions align, SMR construction could begin in 2030, with inauguration by 2038.

Where? - The study proposes building a modular PWR-type nuclear reactor in northeastern Brazil, prioritizing low-income, low-HDI areas. Alagoas was selected due to its lowest HDI (0.631) and the second-lowest household per capita income (R$ 777) in the country [14]. Brazil's nuclear facility licensing is regulated by CNEN, requiring a "Site Report" covering land use, facility capacity, radioactive inventory, and safety systems [16]. The site selection follows the EPRI Siting Guide, using a decision tree approach: exclusion criteria, candidate region identification, suitability assessment, and final site selection [13]. Eletronuclear applied this method with Fuzzy Logic, evaluating 40 candidate areas and narrowing them to four viable regions based on demographic, seismic, meteorological, and ecological factors. Figure 3-A: General map of water-supplied regions (areas 1-4 in green). Figure 3-B: Focus on Alagoas, analyzing physical and geological factors. Figure 3-C: Zoom on Region 3, defining the isolation zone. Figure 3-D: Highlights two optimal construction sites in yellow[29]. The selected area (Figure 3-D) near the São Francisco River provides a balance between low population density and logistical feasibility, ensuring efficient energy distribution [13]. Studies confirmed the region's safety regarding meteorology, geology, and hydrology. SMR implementation in Brazil is not limited to the Northeast. ABDAN is working with FINEP and Diamante Energia to replace coal-fired power plants with SMRs, aligning with PNE goals [30]. The Jorge Lacerda Thermal Power Complex (Santa Catarina) is being evaluated as a pilot project, potentially setting a model for transition by 2040.

Figure 1: Images of the Site Selection Process using the EPRI Methodology and Applied Fuzzy Logic.



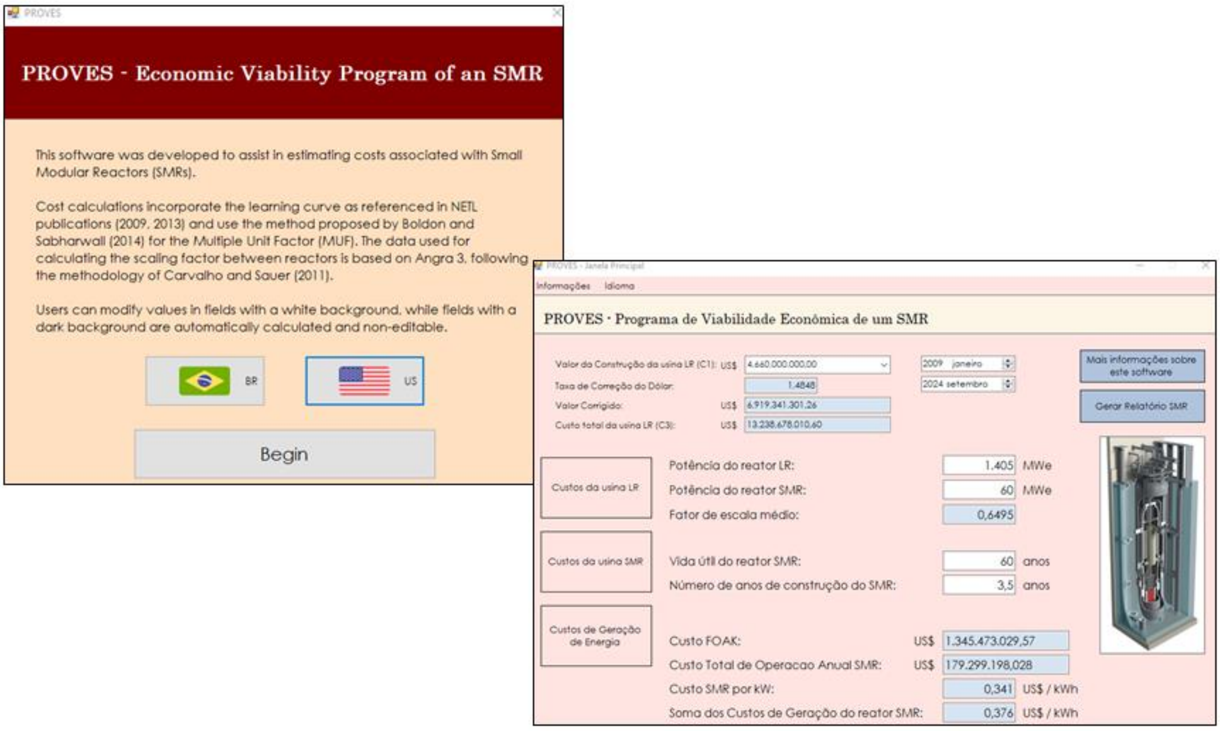
Source: Barros et al., 2021.

Who? - The construction of nuclear reactors in Brazil involves several key actors and responsibilities. Nuclebrás Equipamentos Pesados S/A (NUCLEP) is primarily responsible for manufacturing essential reactor components like pressure vessels and steam generators [15]. The Brazilian state, through CNEN, oversees licensing and regulation to ensure safety [16]. Eletronuclear operates Angra 1 and 2, collaborating with NUCLEP to meet technical and safety standards [31]. Additionally, the Institute of Energy and Nuclear Research (IPEN) supports nuclear projects with research and technological development [32]. Eletrobrás represents the nuclear industry, with a history of constructing reactors such as Angra 1, 2, and the under-construction Angra 3 [31]. The private sector may also contribute through partnerships, while government tax incentives, including exemptions and subsidies, aim to attract investments in this high-cost, technologically complex sector [1].

How? - Answering the question "How will it be done?" involves a detailed analysis of nuclear energy expansion in Brazil, focusing on nuclear reactors as a strategic investment. The PNE 2050 outlines several strategies for this expansion, considering the inclusion of PWR-type SMRs. These reactors are seen as crucial for providing complementary power due to their flexibility and safety, significantly contributing to the additional energy supply [1][2]. To meet the needs of PNE 2050, more advanced models for analyses will be required, considering not only the average and peak energy demand but also changes in consumer preferences over time. Utilizing more modern computational tools, with detailed analysis over time and in different locations, can provide more accurate forecasts [1]. The main challenges in nuclear expansion include effective communication with society about plant safety and used fuel storage. Transparent communication strategies are crucial to overcoming risk perceptions [1]. Additionally, institutional and regulatory adequacy is crucial to resolve legal issues and make nuclear ventures more attractive. This includes the flexibilization of Union monopolies in the nuclear chain and the promotion of Public-Private Partnerships [31]. The safety of nuclear facilities will be ensured through comprehensive designs that cover all phases of the fuel cycle, developing effective decommissioning strategies, and extending the life of existing reactors [1][33]. It is also essential to expand knowledge about mineral resources applicable to the nuclear fuel cycle, such as the uranium mineral basin of Lagoa Real in Bahia, for a long-term strategy. In summary, the strategic approach outlined in the PNE 2050 recommendations aims to create a conducive environment for nuclear energy expansion in Brazil. This involves a combination of effective communication, institutional adequacy, rigorous safety, and mineral resource exploration, balancing challenges with strategic opportunities for a sustainable and efficient energy future.

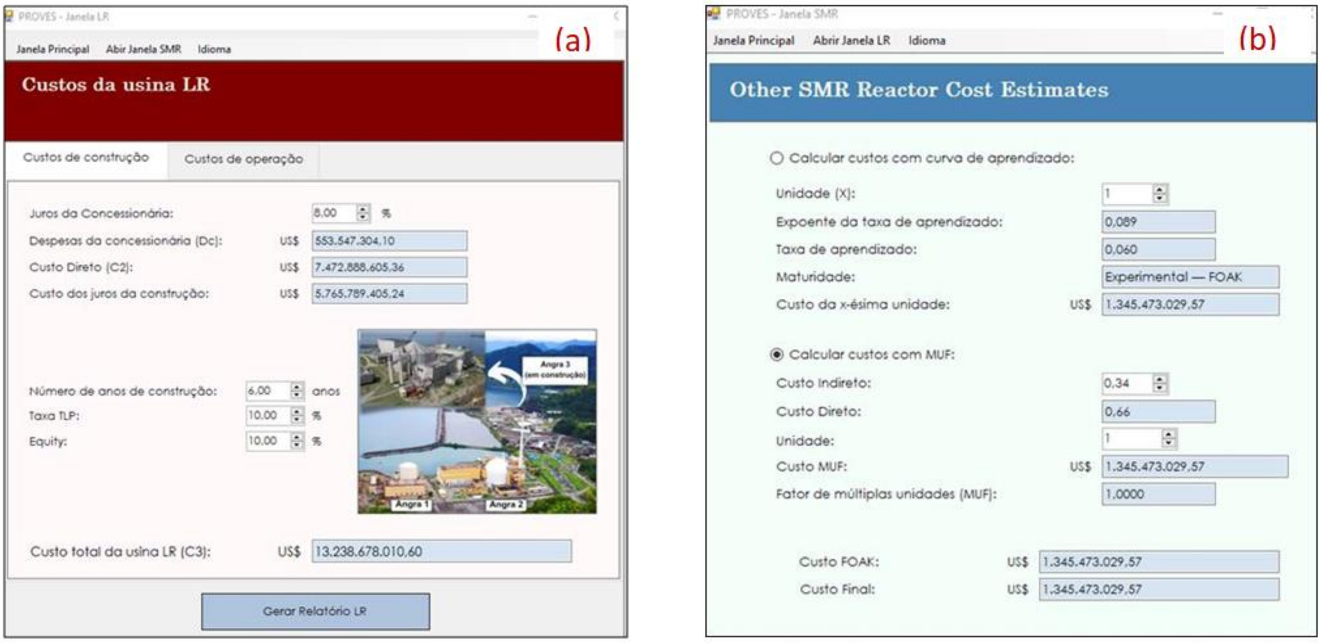
How Much? - To answer this question was developed PROVES, whose main screen was presented previously. As an example of the economic feasibility calculation for the 120 MW(e) of a SMR (PWR), the large-scale Angra 3 PWR reactor will be used, with adjusted costs from 2009 dollars to 2024, totaling US$ 6,803,600,000 with a capacity of 1,405 MW(e). The program developed in this study, PROVES, will be used for this calculation. By correctly filling in the input fields on the main screen shown in Figure 4, the cost of a SMR can be obtained, as shown in Figures 4, 5and 6 show auxiliary screens for PROVES.

Figure 2: Economic Viability Calculation of a PWR-Type SMR (PROVES)



Source: Pereira, V. S. A. and Fang, O. S. K., 2024.

Figure 3: (a) Reference Large Reactor properties and costs and (b) FOAK Cost for SMR (60 MWe) - PWR



Source: Pereira, V. S. A. and Fang, O. S. K., 2024.

The access to PROVES, which was developed in this work, can be done through the following link: https://github.com/kaesujo/PROVES/releases

3.1. Summary of the Application of the 5W2H Methodology

Based on the answers to the questions of the 5W2H methodology applied to the installation of NuScale in a needy region of Brazil, it was possible to compile this information in a summarized form in Table II.

Table 1: 5W2H – Implementation and Construction of a PWR SMR in Brazil

QUESTION	ACTION
What?	• Investment in base factories and the implementation of a PWR-type SMR in Brazil; • Investment for public acceptance of nuclear reactors; • Development of underserved areas that could host such a project; • Increase energy production according to the PNE 2050 deadline; • Energy diversification and reduction of greenhouse gas emissions.

QUESTION	ACTION
When?	• Improvement in schedules due to modularization, reducing the construction time of an SMR-type reactor by up to 40%; • Ideal situation: If started in 2030, completion is expected by 2038.
Why?	• Supply of electricity from a clean, greenhouse gas-free source for the country's development; • Need to produce more energy for future years; • Research shows that the development of SMRs is a good investment for energy and environmental security.
Where?	• Using the site selection method following the EPRI Siting Guide criteria, it has been demonstrated that the Northeast can receive such an investment; • Construction of a modular PWR nuclear reactor in the northeastern region of Brazil, specifically in Alagoas.
Who?	• NUCLEP: manufacturing of the main components of nuclear reactors; • CNEN: licensing and regulation of nuclear activities; • Eletronuclear: operation and collaboration with NUCLEP; • IPEN: technical and scientific support; • Public-private partnerships and tax incentives to attract investments.
How?	• Strategies outlined in PNE 2050, using PWR-type SMRs; • Development of advanced models and modern computational tools; • Effective communication with society about plant safety; • Institutional and regulatory adequacy, promotion of Public-Private Partnerships.
How Much?	An example of the economic viability calculation for NuScale of 60 MW(e), using the calculation program developed in this work (PROVE) was US$ 1,345,473,029.57 and the cost of energy generation is 0.376 US$/kWh, considering the year 2024.

Source: Pereira, V. S. A., 2024

4. CONCLUSIONS

The construction of nuclear reactors, especially PWR-type SMRs, is promising for Brazil due to the growing electricity demand and the need to diversify the energy matrix. The study employed the 5W2H methodology to conduct a preliminary analysis that covers technical, economic, regulatory, and social aspects. Institutions such as NUCLEP, Eletronuclear, and CNEN, along with private partners, have the necessary expertise to lead these projects safely and efficiently. Moreover, transparent and educational communication is essential to gain public acceptance, highlighting the benefits of nuclear energy in terms of safety, sustainability, and environmental impact. Finally, this study is just a starting point, requiring further in-depth analyses to address all the complexities of implementing nuclear reactors in Brazil. The preliminary costs involved for NuScale (PWR) of 60 MW(e), according to the PROVE program developed in this work, reach around 1,345,473,029.57 and the cost of energy generation is 0.376 US$/kWh, considering the year 2024.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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