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Economic Evaluation of Hydrogen Production Using a Small Modular Nuclear Reactor (SMR) as an Energy Source

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Abstract: Hydrogen is an important energy vector for the global energy transition. Due to its low carbon emissions, it has become a central subject of study for major nations. Small modular nuclear reactors (SMRs) represent an innovative approach in the nuclear field. This technology provides greater versatility, safety, and lower costs for energy production on a reduced scale compared with large nuclear reactors (LRs). This paper presents an economic evaluation of hydrogen production using a Small Modular Nuclear Reactor (SMR) as the primary energy source. The methodology uses the Hydrogen Economic Evaluation Programme (HEEP) software provided by the International Atomic Energy Agency (IAEA) to estimate the levelized cost of hydrogen production (LCOH, in USD/kg of H2) using SMRs. The model considers intrinsic characteristics of the power generation plant and of the Polymer Electrolyte Membrane (PEM) plant, the latter supplied by Hytron/NEA. To validate the methodology, it was necessary to evaluate the hydrogen production costs for a large reactor on the market, the AP1000 from Westinghouse. Based on these results, a 77 MWe NuScale SMR built under the same inflationary conditions as the LR was evaluated to avoid significant distortions in the results. For a realistic evaluation, cost studies provided by international institutions such as MIT and the U.S. Department of Energy`s Nuclear Energy Administration (DOE/NEA), and, when possible, by NuScale and Westinghouse, the companies responsible for the reactors being analyzed, were used. Preliminary results show that SMRs present significant competitiveness in terms of levelized cost of hydrogen compared to alternative clean energy sources such as renewable, including solar photovoltaic, solar thermal, and wind power. Due to the versatile, scalable, continuous, predictable, and dispatchable generation profile of SMRs, the cost difference found is negligible. This validates the potential of nuclear technology, which plays a strategic role in the energy transition both globally and in Brazil, and reinforces the importance of in-depth assessments on the subject.

Keywords: SMR Reactors, Hydrogen Economy, Cost Analysis, Energy Transition.

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Avaliação Econômica da Produção de Hidrogênio Utilizando um Reator Nuclear Modular Pequeno (SMR) como Fonte de Energia

Resumo: O hidrogênio é um importante vetor energético para a transição energética mundial. Por possuir baixa emissão de carbono, tornou-se o principal objeto de estudo das grandes nações. Os reatores nucleares modulares pequenos (SMRs, in English), por conseguinte, apresentam caráter inovador na área nuclear. Essa tecnologia traz mais versatilidade, segurança e menores custos para a produção de energia em uma escala reduzida quando comparada a reatores de grande porte (LR, Large Reactor in English). Esse trabalho apresenta uma avaliação econômica da produção de hidrogênio utilizando um SMR como fonte de energia primária. A metodologia consiste na utilização do software, disponibilizado pela Agência Internacional de Energia Atômica (IAEA, in English), Hydrogen Economic Evaluation Programme (HEEP), para estimar o custo nívelado da produção de hidrogênio (LCOH, em USD/kg de H2) usando SMRs. O modelo considera características intrínsecas à planta de geração de energia e da planta de eletrólise por membrana polimérica (PEM, in English), esta fornecida pela Hytron/NEA. Fez-se necessário, para validar a metodologia, avaliar os custos de produção de hidrogênio para um reator de grande porte sólido no mercado, o AP1000, Westinghouse. Com esses resultados, foi avaliado um SMR construído sobre as mesmas condições inflacionárias do LR para não haver distorções significativas nos resultados, o NuScale de 77 MWe. Para uma análise fidedigna à realidade, utilizaram-se estudos de custo disponibilizados por entes internacionais como o MIT e o Departamento Nacional de Energia Atômica dos EUA (DOE/NEA) e, quando possível, pela NuScale e Westinghouse, empresas responsáveis pelos reatores a serem trabalhados. Resultados preliminares mostram que o SMR apresenta relevante competitividade em termos de custo de hidrogênio quando comparado a fontes alternativas de energia limpa, como a solar térmica, solar fotovoltaica e eólica. Devido ao caráter versátil, escalável e de geração contínua, previsível e despachável dos SMRs, a diferença encontrada torna-se pouco relevante. Isso valida o potencial da tecnologia nuclear que, por sua vez, apresenta papel estratégico para a transição energética tanto no mundo como no Brasil, além de reforçar a importância de avaliações profundas sobre o tema.

Palavras-chave: Reatores SMR, Economia de Hidrogênio, Análise de Custo, Transição Energética.

1. INTRODUCTION

With the growing need for carbon-free energy sources, the energy transition emerges as a solution to address the climate challenges of the century. Hydrogen is the energy vector key in this process, since it possesses remarkable properties and versatility, with significant potential for integration into different types of energy sources, particularly nuclear [1].

The Small Modular Nuclear Reactors (SMRs) represent an evolutionary development in the nuclear field, introducing innovations in safety, cost, and flexibility. Modularization brings versatility and efficiency to meet specific targets of the production chain [2]. This technology can be deployed in remote locations as well as in already existing infrastructures, offering major potential for low-carbon energy production [2].

In this scenario, Brazil emerges as a natural candidate for the new global trend toward low-carbon hydrogen production. The Brazilian Ministry of Mines and Energy (MME) plans for Brazil to become the world's largest exporter of hydrogen by 2030 [3] and by 2050 to build additional pressurized water reactors (PWRs), including SMRs, that can contribute to hydrogen production [4]. These initiatives are known as PNE30 and PNE50, reinforcing the need for studies on the coupling of both technologies.

Furthermore, important milestones have already been reached. It was approved in the National Brazilian Congress, the Hydrogen Legal Framework, which officially establishes incentives for the industry, such as the Special Incentive Regime for Low-Carbon Hydrogen Production (Rehidro) and the creation of the Low-Carbon Hydrogen Development Programme (PHBC) [5].

This demonstrates the commitment of the Brazilian State to become a leader of the world's emergent market that will ensure the success of Brazil not only as a major global economy but also as an important vector of the energy transition in the world.

Therefore, this project explores the economic feasibility of hydrogen production using nuclear energy as the primary source, with both technologies already developed and implemented in Brazil, through electrolysis and pressurized water reactors (PWR).

With the need for alternatives in hydrogen production, SMRs have emerged as a natural choice due to their versatility in meeting this demand. This technology has been explored worldwide, and many economic powers are engaged in a race to develop SMRs with lower costs and greater efficiency. For this reason, it is necessary to conduct a parametric study to assess the potential of SMRs in hydrogen production.

In an initial analysis, a reference reactor was required to validate the proposed methodology. AP1000, a large nuclear reactor (LR), was selected. This choice is justified by the fact that the AP1000 is well established in the global market and provides solid parameters for reliable data analysis. Moreover, these specific plants experienced significant challenges during the construction, resulting in a higher cost than would typically be expected in a developing country.

The SMR selected was the NuScale 77 MW_e VOYGR unit, also under construction in the United States, in order to ensure isonomic economic data. This SMR has faced a challenging construction process, as the innovative perspective of being a First of a Kind (FOAK) entails the absence of an established production chain, which represents a major obstacle during construction.

For hydrogen production, the selected method for analysis is the Polymer Electrolyte Membrane (PEM) electrolysis, as it offers robust data and is widely used around the world. The electrolyzer is provided by Neuman & Esser Group (NEA)/Hytron, a partnership between NEA, a German company, and Hytron, which operates in both the national and international markets. The electrolyzer power was set at 5 MW, according to official company documents [6].

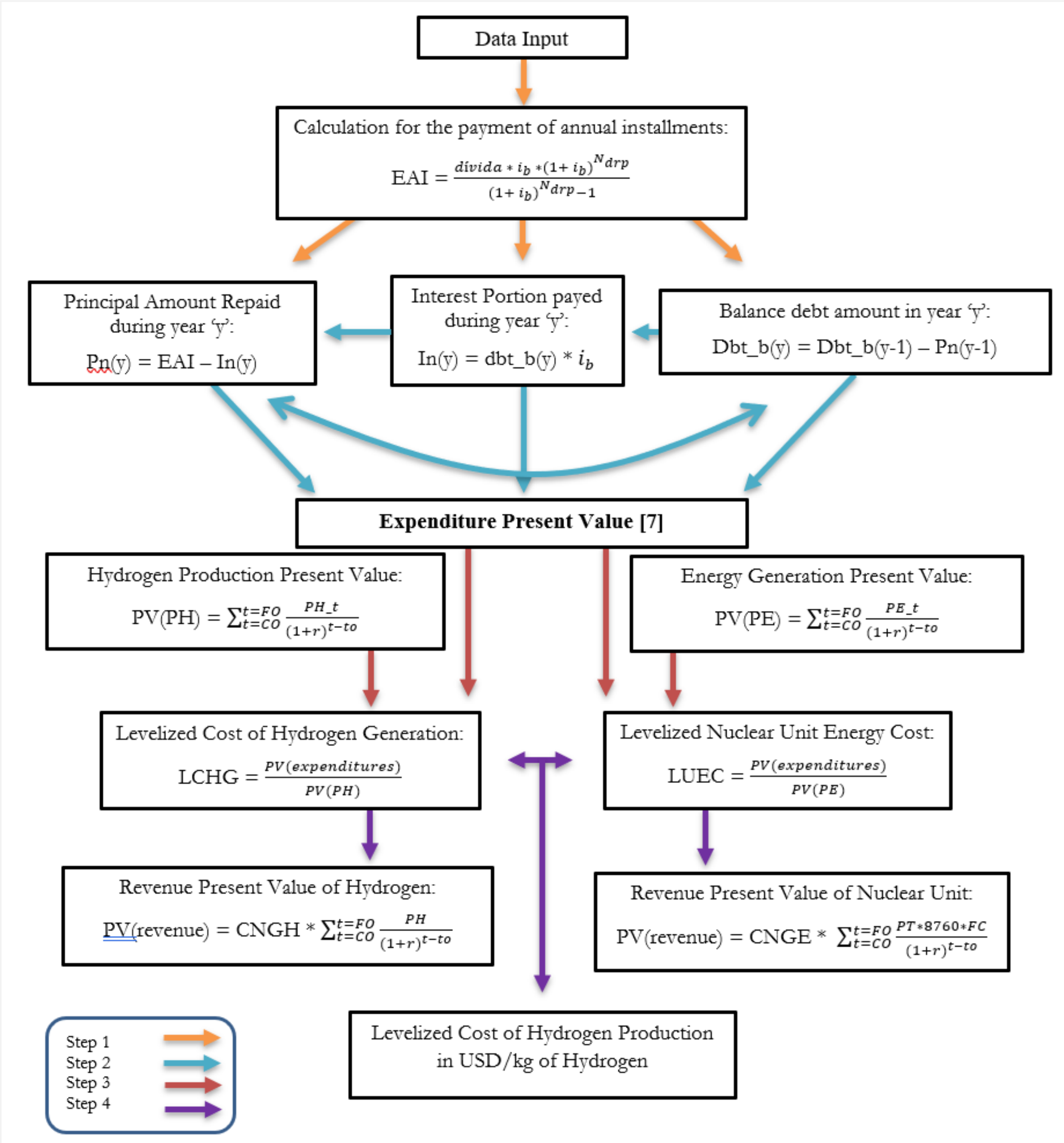
The location for the construction of the plant was defined as developed Western countries, such as the United States and several European nations. Currency stability and steady economic growth were important factors in this decision in order to avoid potential market distortions.

2. MATERIALS AND METHODS

For the conduction of the analysis, the Hydrogen Economic Evaluation Programme (HEEP) software, developed by the International Atomic Energy Agency (IAEA), was employed. The evaluation aims to provide a detailed study of the feasibility of using nuclear energy for low-carbon hydrogen production. The process combines real data from official sources with specific models of hydrogen production, such as the PEM electrolysis.

The input data in HEEP are divided into two main categories: engineering and economic data. The intrinsic programming of the HEEP software is represented in detail in the flowchart below (Figure 1).

Figure 1: Methodology Flowchart



Source: [7]

The flowchart begins with the normalization of economic data, considering key factors such as inflation rates and taxes related to the evaluated period. Once the real data are calculated, it is possible to estimate the Equivalent Annual Interest (EAI), which accounts for the annual borrowing interest rate (ib) and the Repayment Period of borrowings (Ndrp).

In the second step, three interdependent parameters are calculated simultaneously. The first is the Principal Amount Repaid during Year 'y' (Pn(y)), obtained by subtracting the Interest Portion Paid during year 'y' (In(y)) from the EAI. The value of In(y) is defined as the product of ib and the Balance Debt Amount in the Year 'y' (Dbt_b(y)). Finally, Dbt_b(y) is defined as the Debt Balance Amount of the previous year (Dbt_b(y-1)) minus Pn(y).

In the third step, all obtained data are used to calculate the Present Values of Expenditure (PV(expenditures)). Due to the complexity of the calculations associated with PV, the flowchart was simplified for easier understanding; the complete set of calculations is presented in the HEEP User Manual [7]. In a parallel calculation, the Present Value of Hydrogen (PV(PH)) and Present Value of Energy Generation (PV(PE)) are estimated.

Both values are defined as a summation that starts in the Initial Year of Operation (CO) and ends at the Final Year of Operation (FO). PV(PH) is calculated by dividing the annual Hydrogen Production in Year 't' (PH_t) by the term (1+r) raised to the power of the difference between the year 't' and the Initial Year (t0). PV(PE) follows the same structure, with the numerator replaced by the Annual Production of Energy (PE_t).

Finally, the prices are levelized by dividing the previously obtained values. The Levelized Cost of Hydrogen Production (LCHP) is given by the PV(expenditure) divided by PV(PH), and the Levelized Cost of Energy Production (LCEP) is obtained by dividing PV(expenditure) by PV(PE).

The fourth and final step provides the result of the hydrogen cost in USD/kg of hydrogen. Furthermore, the Present Value of Revenue (PV(Revenue)) is calculated as a levelized multiplication by a summation similar to the one used in the previous levelized calculations. The difference lies in the denominator of the nuclear plant calculation, where the numerator consists of the product of the reactor's electric power in year 't' (PT), the Capacity Factor (CF), and the constant value of 8760, which represents the hours in a year.

In this initial study, a simplification was made regarding the parameter associated with hydrogen transport and storage after production. These expenditures are relevant and will be considered in future analysis.

In addition, it is important to present the values obtained for both nuclear power plants used in this study. The information is summarized in Table 1:

Table 1: Technical and Economic Parameters of the Nuclear Plant

Entry Parameters	AP1000	NuScale
Thermal Power (MW_{th})	3415.00	250.00
Electrical Power (MW_e)	1115.00	77.00
Initial Fuel (kg/Plant)	95958.28	5624.52
Annual Fuel Feed (kg/Plant)	21324.10	934.42
Capital Cost (USD)	1.04×10^{10}	3.73×10^{8}
Fuel Cost (USD/kg)	2935.00	2935.00
Electrical Generation Center Cost (% of Capital Cost)	24.70	3.80
O&M Cost (% of Capital Cost)	1.80	3.10
Decommissioning Cost (% of Capital Cost)	4.82	3.60
Capacity Factor (%)	93.00	95.00

Source: [6] and [8-17]

A refueling cycle of 18 months was adopted for the AP1000 and 24 months for the NuScale SMR. In each refueling outage, one-third of the existing fuel is replaced. Operation and Maintenance (O&M) costs are estimated at an average of 24.35 USD/MW_e [8], requiring only the calculation of the total energy produced over the period and the capacity factor of 93%. Percentages applied to the capital cost were calculated based on a total capital cost calculation of 158 USD/MW_e as total [8].

In addition, the mean cost of UO_2, enriched <4.95%, was considered as 9 USD/MW_e [8]. A separation factor of 30 years was adopted until the end of the capital cost, followed by 50 additional years for O&M and decommissioning. The usual reconditioning period associated with a mid-life power plant was also considered.

Decommissioning cost was initially estimated at 4000 USD/kW in a 2009 study [18]. However, the Vogtle units 3 and 4 faced some construction challenges, reaching 11000 USD/kW [19]. This value is nearly three times higher than the estimate from the 2009 study, highlighting the impact of the COVID-19 pandemic.

Furthermore, the decommissioning cost was adapted to three times the value of 7×10^8 USD expected [18], summing up to 2.1×10^9 considering a linear progression of the cost, a great approximation even knowing the impact of decommissioning has a less representative value in the final calculation as shown in the HEEP user's manual [18].

The electric central power generation is usually adopted as 20% of the total capital cost in PWRs [20]. The reference study considered three PWRs reactors with very similar electrical power outputs when compared to the AP1000. When the mean value of these three reactors is calculated, it corresponds to 24.7% of the capital cost, which coincides exactly with the base input value adopted in HEEP.

Naturally, the economic data were considered based on the construction location of the nuclear units, corresponding to a discount rate of 8% and aggregated taxes of 40% [8]. An inflation rate of 2.5% was assumed for the United States, with no economic recession considered.

For the reconditioning calculation, a value of 6.25 USD/MW_e was adopted after the reconditioning period, usually assumed to occur after 30 years of operation [19]. This value is also confirmed in an IAEA manual of good practices for reconditioning in Pressurized Heavy Water Reactors (PHWRs) [13].

This type of reactor operates similarly to traditional PWRs, with the main difference being in moderation, since it uses deuterium instead of regular light water. The construction time is typically assumed as 5 years, with a total operation lifetime ranging from 60 to 80 years, as reported by Westinghouse [13, 21]. For this analysis, an 80-year operational lifetime and a 5-year construction time are adopted, considering optimistic scenarios.

With all the nuclear unit's data collected, the next step is hydrogen generation through PEM electrolysis, one of the main methods available worldwide, noted for its high efficiency and industrial-scale production capability [6]. The companies NEA/Hytron are responsible for the development of the hydrogen generation electrolysis plant. The corresponding data are represented in Table 2:

Table 2: Technical and Economic Parameters of the Electrolysis Plant

Entry Parameters	Hytron/NEA
H_2/Unity Generation Plant (kg/Year)	7.65x10^5
Necessary Power (MW)	5.00
Capital Cost (USD)	6.50x10^6
O&M Cost (% of Capital Cost)	7.00
Decommissioning Cost (% of Capital Cost)	0.20
Capacity Factor (%)	97.00

Source: [6], [12] and [22-23]

The data are associated with plants built in the United States and Europe. The costs showed little variation in both regions due to their economic stability, similar infrastructures, and comparable production chains [22].

O&M and Decommissioning costs are based on two main studies [12, 23], both converging to 7% of the capital cost. The calculation considers a 97% capacity factor, 5 MW of required power, 7.65x10^{5}kg of hydrogen produced annually [6], and 1000 USD/kWh to estimate the capital cost [22].

With all the initial data collected, it was possible to estimate the LCOH. This value can be altered by some changes in specific parameters. Therefore, a parameter sensitivity analysis was conducted to evaluate how variations would impact the LCOH. In this study, all the parameters were kept constant except for the one selected for variation. The analysis included some non-variable parameters from HEEP to identify which factors exert the greatest influence.

The analysis was performed by recalculating the LCOH with five stages of increase and five stages of decrease. The modifications were defined as 10%, 25%, 50%, 75%, and 100% of the base value. This approach made it possible to determine which parameter had the greatest influence on the result and represent these variations graphically using a Python script, allowing for clearer identification of patterns.

For the data analysis, Excel and Python were employed to carry out detailed studies of the evaluated parameters. This procedure enables the identification of specific patterns in the datasets and graphically demonstrates the behavior of certain parameters in greater depth.

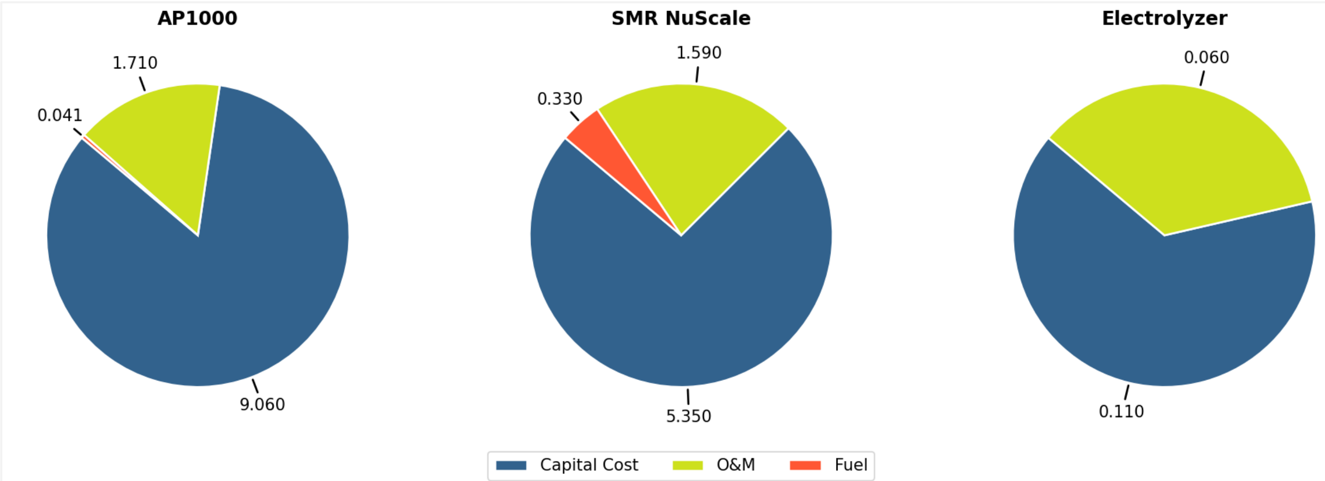
3. RESULTS AND DISCUSSIONS

Using the data obtained from the AP1000, the 77 MW_e NuScale SMR, and the 5 MW Hytron/NEA electrolyzer, the results observed were consistent with initial expectations. The already well-established Vogtle units 3 and 4 showed a LCOH of 11.25 USD/kg of hydrogen. This value is consistent with the difficulties faced during the construction process of the nuclear facility [8].

In contrast, the NuScale SMR showed a significantly lower LCOH, reaching 7.27 USD/kg of hydrogen. This reduction is mainly due to the substantially lower overall cost of the SMR, particularly the levelized cost of energy production per $MW_{e,}$ which incorporates all relevant parameters in its calculation [10] and [19].

Both values were calculated using real economic data, including the inflation rate. If these real parameters were excluded, a significantly lower LCOH would be obtained. The AP1000 value would decrease to 7.71 USD/kg, while the NuScale SMR would result in a 5.35 USD/kg of hydrogen. Figure 2 presents the nuclear and hydrogen units cost distribution as separated in HEEP's calculations in real values:

Figure 2: Cost Distribution in Nuclear and Hydrogen Units



Source: The Authors.

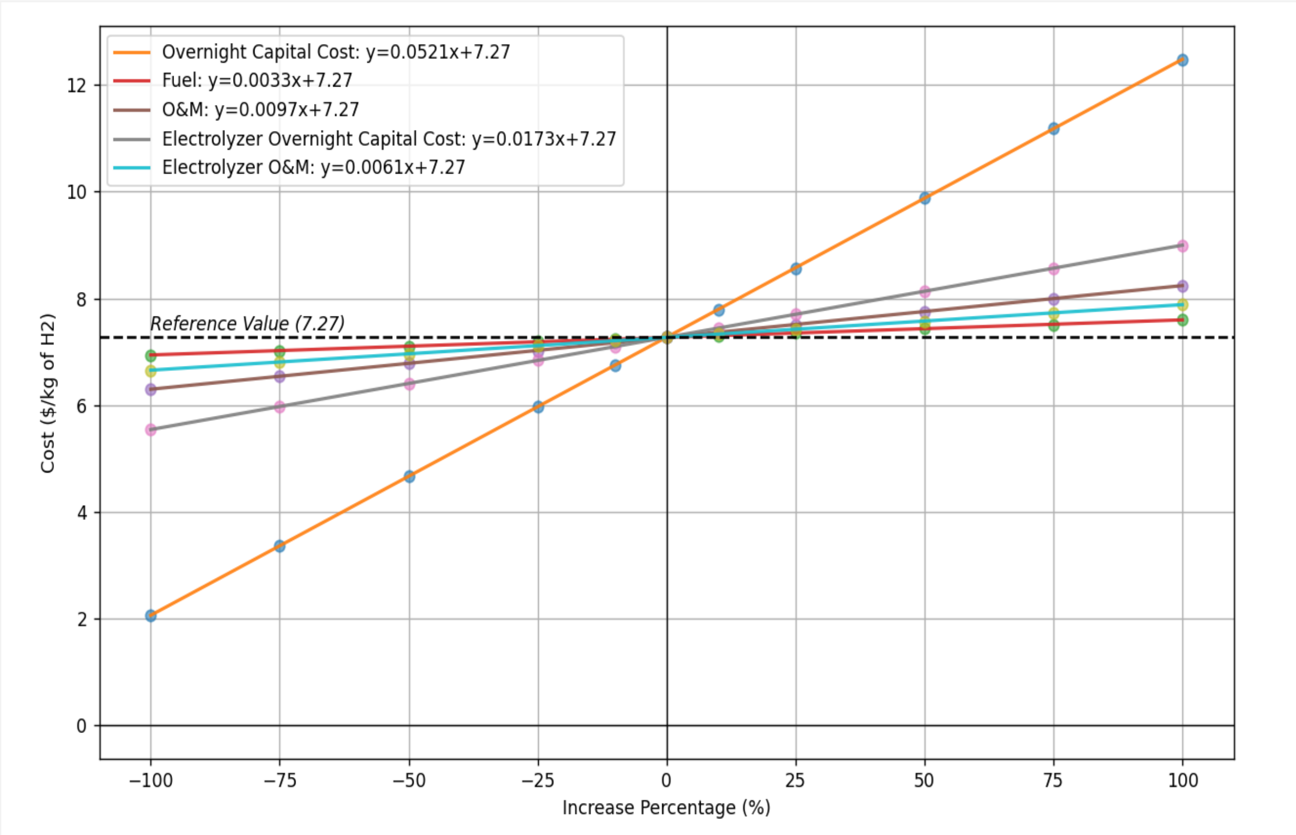
The Capital Cost has a major impact on the final cost of production, due to its higher absolute value. Nuclear facilities usually present higher Capital Costs because of the substantial initial investment, which contributes significantly to higher Capital Cost values [19].

The electrolyzer cost is more balanced, but Capital Cost still represents the largest share in the total value calculation. It is also evident that the hydrogen unit has a significantly lower cost than the nuclear one, since hydrogen production through PEM electrolysis is less complex and easier to maintain when compared to nuclear power generation.

A parametric study was made to verify the parameter variations through significant individual changes. The main parameters evaluated in this parametric study were: Overnight Capital Cost, Fuel Cost when applicable, O&M, for both nuclear and electrolysis units. The study showed a significant difference in the overnight cost of the nuclear facility, as expected. The increase in the value is due to its higher cost compared to other parameters.

The study showed a linear pattern in the key parameters valuated, as shown in Figure 3, with the linear adjustments made to construct the graph with a linearity of 0.9999 out of 1, demonstrating an almost perfect linear fit:

Figure 3: Parameter Variation of Hydrogen Cost



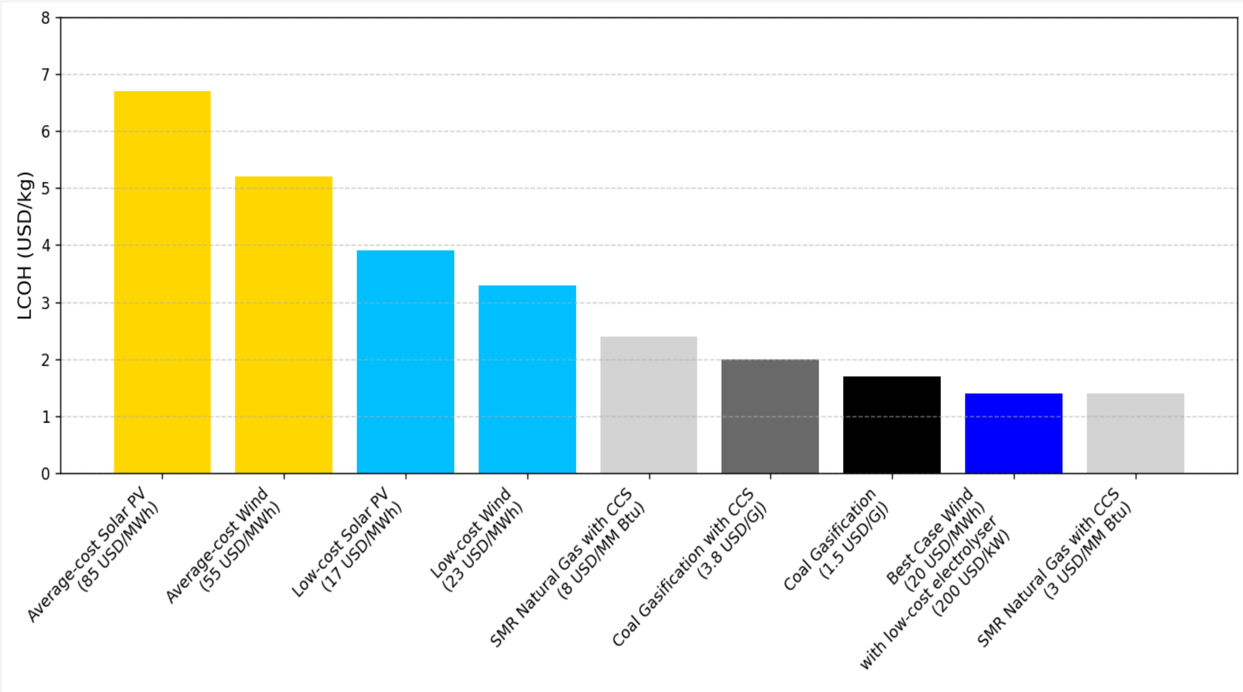
Source: The Author.

In addition to the linear slopes found in Figure 3, other parameters were calculated but present no variation, staying constant during all five stages of increase and decrease of values. These parameters were: Capital Cost for Electricity Generation Infrastructure, and Decommissioning Cost of both nuclear and electrolysis units.

The constant slopes were not considered in the graph due to redundancies in data presentation. The slope with the reference value can stand for the constant parameters retrieved from the graphs because their numerical value is the same.

With all the data, it is possible to infer that the SMR is very competitive and cheaper than the LR used to evaluate hydrogen production. When compared to other primary energy sources, the SMR presents a competitive value, as shown in Figure 4:

Figure 4: Hydrogen Production Cost with Different Primary Energy Sources



Source: [24].

Figure 4, based on a Canadian study [24], presents common ranges of hydrogen cost using different primary energy sources. When evaluated, the range stays between the average photovoltaic solar panels, 7 USD/kg of hydrogen, and SMR Natural Gas, standing close to 1.5 USD/kg of hydrogen. The values are close to the 7.27 USD/kg of hydrogen found in this study. The higher price of nuclear technology is justified by its high reliability, non-intermittency, and low-carbon emissions, which are the main advantages when compared to the other mentioned energy sources that usually do not have those advantages. As an example, solar PV and wind power suffer from intermittency, and natural gas for the high-carbon emissions.

With the values encountered for the SMR hydrogen production, Brazilian applications can be examined. Brazil's territory is vast and usually lacks on-grid systems that cover all the territory. The SMRs come as a solution with competitive prices, predictable energy production, and a reliable energy source for hydrogen production.

Inflation rates, delays, and higher costs than usual for a developed country indicate that the units chosen to conduct this study approximate the situation of a non-developed country, such as Brazil. With these assumptions, the results can be brought to the Brazilian scenario without many accuracy losses, showing an optimistic scenario for its application.

4. CONCLUSIONS

In this study, it was used as a methodology developed by the IAEA for economic analysis of the feasibility of hydrogen production using a nuclear reactor as a primary source of power. The PEM electrolysis was used as the source of hydrogen production.

Initially, the use of the Vogtle units 3 and 4 and VOYGR nuclear facilities, as well as the electrolyzer from Hytron/NEA, presented an accurate study of possible scenarios of hydrogen production integrated with nuclear technology. With that, crucial parameters were determined in both plants for a more detailed and precise analysis.

Considering that the PWRs, technology that is been studied to Brazilian nuclear expansion in PNE50, and the electrolyzer, developed by a Brazilian company, Hytron, the results are relevant to the Brazilian scenario in medium and long-term planning projects. Both technologies are being studied for future energy expansions in Brazil, making it a good reference to the real Brazilian market.

The Cost study is consistent with previously observed studies in the international experience, with a small difference in the prices due to the chaotic scenario of Vogtle 3 and 4 construction and the FOAK characteristics of the NuScale SMR, which justifies the higher price.

With the addition of specific inflation and discount rates of the locality, an increase in price is already expected in the production cost of the facility. The challenges of the inflation rates and the natural delay in the construction represent the most difficult scenarios to predict, because they are, in fact, unpredictable depending on multiple variable factors such as politics. Furthermore, studying a nuclear unit immersed in these problems is a smart choice when it comes to a comparison between a non-developed country, such as Brazil, and a developed country, such as the United States.

Small modular nuclear reactors are a promising alternative for national investment in clean energy technology in Brazil. The versatility of this type of reactor can ensure a reliable energy supply to remote locations through the use of floating nuclear facilities, such as the Akademik Lomonosov, already implemented by the Russian government. This approach facilitates the delivery of large amounts of energy to isolated regions, addressing a major challenge in the Brazilian energy infrastructure.

Furthermore, the estimated values are for FOAK reactors. With modularization and the creation of a dominant production chain, prices will eventually fall to an even more competitive level.

Finally, it can be concluded that there is economic viability in using SMRs as a primary energy source for hydrogen production and that Brazil has great potential to be a protagonist in the development of this revolutionary technology worldwide and to be a leader in the global energy transition.

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CONTRIBUTORSHIP

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Writing – review and editing: V.P.F.; F.R.A.L.; C.J.C.M.R.C.; D.G.R.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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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