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HYDROGEN PRODUCTION EFFICIENCY COUPLED WITH DIFFERENT SMALL MODULAR NUCLEAR REACTOR TECHNOLOGIES

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ABSTRACT

This work compares two small modular nuclear reactor projects , NuScale and HTR-PM, in terms of their hydrogen production systems in cogeneration with water desalination. The comparison is made by evaluating the projects coupled to conventional electrolysis systems and a Cu-Cl thermochemical cycle for hydrogen production. In parallel, the cogeneration of water production through a desalination system using MSF is considered. The global efficiencies of the flow charts are determined with the utmost scientific rigor by constructing a computational model in a chemical process simulation code. The present analysis provides optimized operating parameters, along with the energy and exergetic efficiencies of the main components of the proposed flow diagram. Finally, a comparison is made between the models considering the technical criteria inherent to each nuclear reactor project.

1. INTRODUCTION

Hydrogen, with its versatility, storage capacity, and potential for integration with other clean technologies, is emerging as a vital energy carrier in the global transition to sustainable energy. The effective reduction of carbon emissions is crucial for improving energy security in the industrial, transportation, and energy production sectors [1]. Conventional electrolysis technology, a primary method for producing hydrogen, is gaining significant attention as a sustainable technique for producing hydrogen without generating carbon emissions. It is particularly efficient when powered by clean energy sources such as solar, wind, or nuclear power. The efficiency of several extensively researched and evaluated electrolysis techniques not only instills confidence but also reassures us about the viability of hydrogen production [2].

Numerous electrolysis methods have undergone thorough research and assessment to achieve effective and environmentally friendly hydrogen generation. Solid Oxide Electrolysis Cells (SOEC), Alkaline, and Proton Exchange Membrane (PEM) technologies have shown significant potential based on the specific electrolyte used and the precise operational temperature range, as cited in reference [3]. A promising method for hydrogen production involves breaking down water molecules through various thermochemical cycles, as outlined in recent investigations [4]. One particularly intriguing cycle is the copper-chlorine (Cu–Cl) process, which has garnered attention due to its lower temperature and production cost. In this thermochemical cycle, water is decomposed into its components, hydrogen and oxygen, utilizing heat or electricity, especially when combined with high-temperature heat sources such as High-Temperature

Reactors (HTR) [5]. Electrolysis and the thermochemical Cu-Cl cycle are notable advancements in hydrogen production, thereby contributing to establishing a sustainable hydrogen economy.

Alkaline electrolysis is a well-established technology for hydrogen production, where water is split into hydrogen and oxygen using an alkaline electrolyte, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH) [1]. This process, driven by electricity, is efficient and scalable but traditionally depends on external power sources, often from the grid. When coupled with nuclear reactors, this technology gains a significant energy efficiency and sustainability advantage. Nuclear reactors, particularly advanced and small modular types, can provide a consistent and large-scale supply of low-carbon electricity. This electricity can be directly used to power the electrolysis process, creating a synergy that maximizes the utilization of nuclear energy and produces hydrogen with a minimal carbon footprint [6].

Integrating alkaline electrolysis with nuclear reactors is particularly attractive as it allows for the continuous production of hydrogen, a key component in the transition to a hydrogen-based economy. The stability of nuclear power, with its ability to generate electricity around the clock, ensures that hydrogen production can proceed uninterrupted, unlike renewable sources dependent on weather conditions. Furthermore, the high operating temperatures of some nuclear reactors can enhance the efficiency of the electrolysis process, potentially reducing the overall energy required to produce hydrogen. This coupling diversifies the utility of atomic energy beyond electricity generation and offers a robust solution to creating clean hydrogen on a large scale, supporting global decarbonization efforts [7].

Small Modular Reactors (SMRs) are an advanced form of nuclear energy technology that highlights safety, cost-effectiveness, and flexibility. Their modular design enables efficient construction and customization to meet specific energy requirements. Unlike large reactors, SMRs are well-suited for combined heat and power generation. They can be deployed in remote regions or integrated into existing energy systems, offering significant potential for reducing carbon emissions and diversifying the global energy mix. Certain SMRs can operate at full power for maximum conversion efficiency when switched for cogeneration. Additionally, employing polygeneration can effectively address the challenges associated with nuclear energy's role as a primary electricity supplier [8], [9], [10], [11].

This paper presents a conceptual design for a hydrogen production system that integrates the NuSCALE nuclear reactor with an alkaline electrolysis system. The design is simulated to assess its technical feasibility, focusing on determining the energy and exergy efficiencies of the process. Additionally, a comparison is made between the proposed system and another hydrogen production method outlined by González et al. (2023) [5], which uses the HTR-PM small modular reactor for hydrogen production and seawater desalination via a thermochemical process. Although these two reactors and hydrogen production methods differ significantly, the comparison provides valuable insights into the advantages and disadvantages of each technology.

2. METHODOLOGY

The NuScale Power Module, developed by NuScale Power LLC, is a small modular pressurized water reactor (PWR-SMR) that received Standard 160MWth (50MWe) Design Approval from the US Nuclear Regulatory Commission (NRC) in 2020 [12]. In 2023, the NRC accepted a second Standard Design Approval (SDA) application for a 6-module power plant configuration powered by an improved 250 MWt (77 MWe) SMR design. In the same year, the manufacturing process for the NuScale power modules began. These modules feature an advanced nuclear design based on established pressurized water-cooled reactor technology, as shown in Fig. 1.

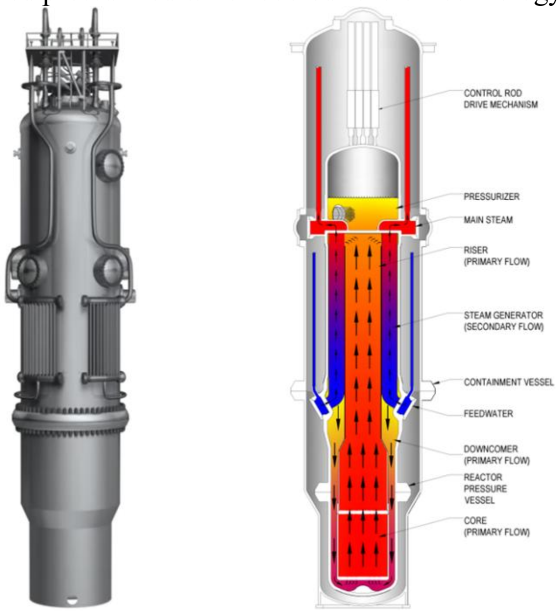


Fig. 1. NuScale Power Module, outside view (left-side), cutaway view (right-side)[14].

Each module (Fig. 1) provides 77MWe in a standard light water reactor configuration, with 2 meters of active fuel length arranged in a traditional 17x17 assembly. The NuScale Power Modules have a design life of 60 years, a refueling cycle of up to 21 months, and a UO2 fuel enrichment of less than 4.95% [13]. Tab. 1 presents the main characteristics of the NuScale Power Plants.

Tab. 1. Overall features of the NuScale Power Plants [15].

Parameter	**Value**
N° of available modules	4, 6 or 12
Net electrical power (per module)	77 MWe
Average linear power density	8.20 kW/m
Reactor coolant system normal operating pressure	12.75 MPa
Core inlet temperature	531.48 K
Core average outlet temperature	587.04 K
N° of steam generators (per module)	2
Steam generator type	Vertical helical tube
Steam generator inlet temperature	421.87 K
Steam generator outlet temperature	580,04 K
Steam generator outlet pressure	3.45 MPa
Steam generator mass flow	67.07 kg/s

One of the standout features of NuScale Power Modules technology is its strategic flexibility to enable the polygeneration concept and align side-by-side electricity generation and multiple non-electrical applications, including hydrogen production, seawater desalination, and district heating. The partnership between NuScale and ENTRA1 is poised to drive the commercialization of this SMR technology, enabling NuScale Power Plants to accommodate up to four, six, or 12 individual NuScale Power Modules [13].

This paper aims to present the development of a computational model designed to assess the feasibility of integrating the NuScale SMR project with an alkaline electrolysis hydrogen production process. Furthermore, we contrasted the findings of the current paper with those of preceding studies conducted with an alternative SMR configuration. The HTR-PM nuclear reactor has been the subject of study concerning its potential for hydrogen production via a thermochemical water dissociation process, as detailed by González et al. (2022) [6]. We developed a computational model to estimate the energy and exergy efficiency of the alkaline electrolysis hydrogen production system using the 4 NuScale power modules. This analysis establishes a baseline for the evaluation of hydrogen production processes.

Fig. 2 illustrates the integration of the hydrogen production process by electrolysis with a NuScale power module. A fraction of the energy generated by the Rankine cycle is delivered to the hydrogen production process while the rest feeds the electric grid. The turbine steam flow goes to a heat exchanger before the condenser, preheating the water before the electrolyzer process. This previous step reduces the energy requirements of the electrolysis process [12].

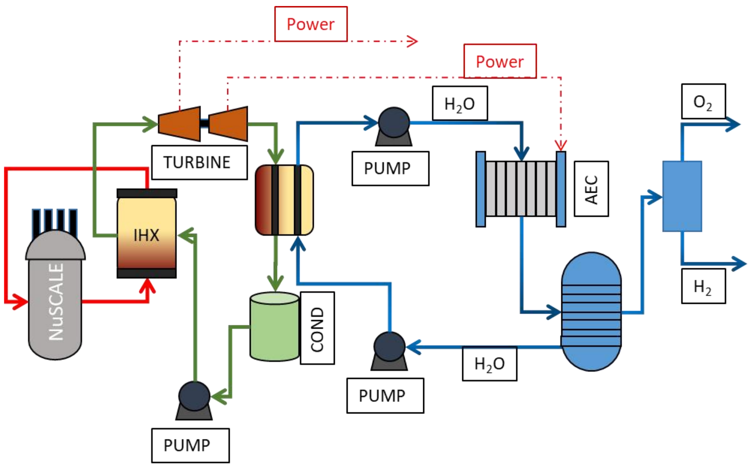


Fig. 2. Schematic representation of the NuScale power module coupled to the alkaline electrolysis process for hydrogen production.

The overall process efficiency is estimated using a chemical process simulator (CPS), assuming the Rankine cycle and the alkaline electrolysis system together. We calculate the exergy destruction rates and the exergetic efficiency of each flow diagram component. These are the assumptions for the building of the process flow diagram:

- We perform a steady-state simulation assuming nominal operating parameters.
- We neglected the components' gravity forces and kinetic energy loss influences.
- The computational model does not account for heat losses in components, pipes, or pressure drops along the pipes.

Given the nature of the simulation, it is necessary to incorporate thermodynamic packages into the CPS model to represent the equation of the chemical components' state and describe the alkaline electrolyzer module. It is set to the Peng-Robinson model [14] and the NRTL (Non-Random Two Liquids) model [15] in Aspen Plus. We model the following mass, exergy, and energy balance equations to ascertain the energy and exergy efficiencies:

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \quad [1]$$

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{in} - \dot{W}_{out} = \sum_{out} \dot{m}\,(h_{PT} - h_0 + h_f) - \sum_{in} \dot{m}\,(h_{PT} - h_0 + h_f) \quad [2]$$

$$\dot{E}x_{\dot{Q}_{in}} - \dot{E}x_{\dot{Q}_{out}} + \dot{E}x_{\dot{W}_{in}} - \dot{E}x_{\dot{W}_{out}} = \sum_{out} \dot{m}ex_{ou} - \sum_{in} \dot{m}ex_{in} + \dot{E}x_d \quad [3]$$

Where $\dot{m}$ is used to denote the mass flow rates, the work rates, the heat transfer rates, the exergy destruction rate, the specific exergy, and the exergy content of the heat transfer rates that can be calculated according to Al-Zareer et al. (2017), and h is the specific enthalpy [16].

3. RESULTS

Fig. 3 shows the chemical process simulator diagram with four NuScale power modules and their energy conversion cycle built in Aspen Plus® (For a clearer understanding of the proposed flow diagram, please refer to the List of Acronyms and Symbols in the attachments).
As previously said, an energy fraction from the Rankine cycle goes to the electrolyzer and other components of the hydrogen production process. This paper assumes that 1/4 of the energy produced from the Rankine cycle goes into the hydrogen production process. This percentage is adopted, and it maintains the same parameter for comparing hydrogen production using alkaline electrolysis and the NuScale power module against the Cu-Cl thermochemical process and the HTR-PM reactor developed by Gonzalez et al. 2019 [17].

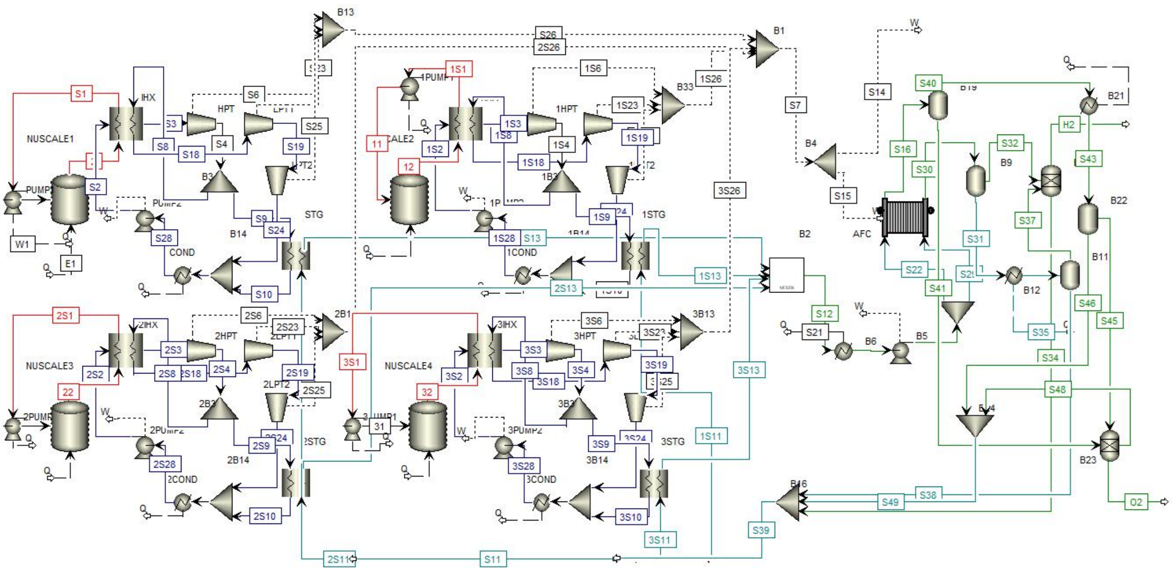


Fig. 3. Four NuScale power modules coupled to the alkaline electrolysis process for hydrogen production using Aspen Plus.

Four Rankine cycles together produce 264.13 MWe, and 66.03 MWe goes to the AEC electrolyzer. We use this result as the electrolysis process dimensioning design parameter described in the next section. We estimate the Rankine cycle efficiency according to the following expression:

$$\eta_{Rankine} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{4 \times \dot{Q}_{NuSCALE}} \quad [4]$$

The electrical power generated by Rankine cycle turbines is calculated by:

$$\dot{W}_{turbine} = 4\times\left(m_{S3}h_{S3} - m_{S24}h_{S24}\right) = 264{,}14MWe \quad [5]$$

By calculating the energy consumed by the four circulation pumps of the Rankine cycle, we can determine the energy efficiency of the Rankine cycle by:

$$\eta_{Rankine} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{4\times\dot{Q}_{NuSCALE}} = 0{,}3796 \quad [6]$$

To determine the exergetic efficiency, we use the expression:

$$\psi_{Rankine} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{4\times(\dot{m}_2 ex_2 - \dot{m}_1 ex_1)} = 0{,}8143 \quad [7]$$

These efficiency values are consistent with the expected ranges for this type of system, given the operational temperature ranges of SMRs [16]. Fig. 4 displays the exergetic efficiency results for the Rankine cycle components. Those with the lowest values are the turbines (HPT, LPT, LPT2) and the heat exchangers (IHX, STG). These components exhibit the highest temperature variations in the flow diagram, explaining their lower efficiency values.

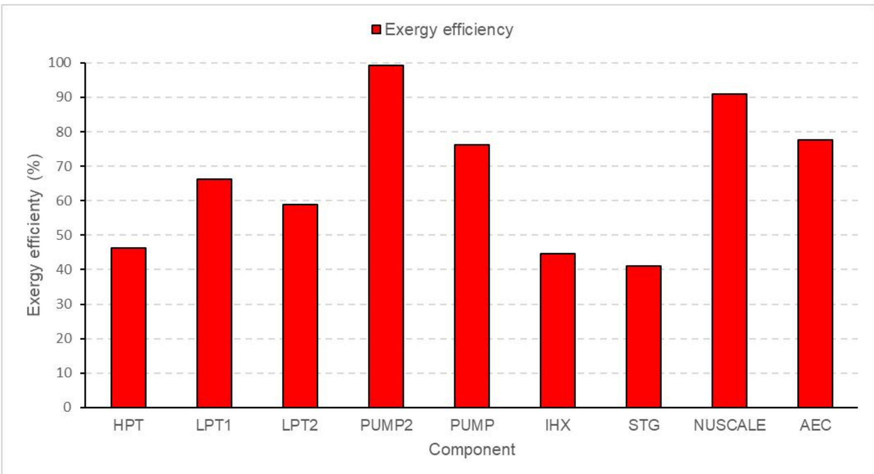


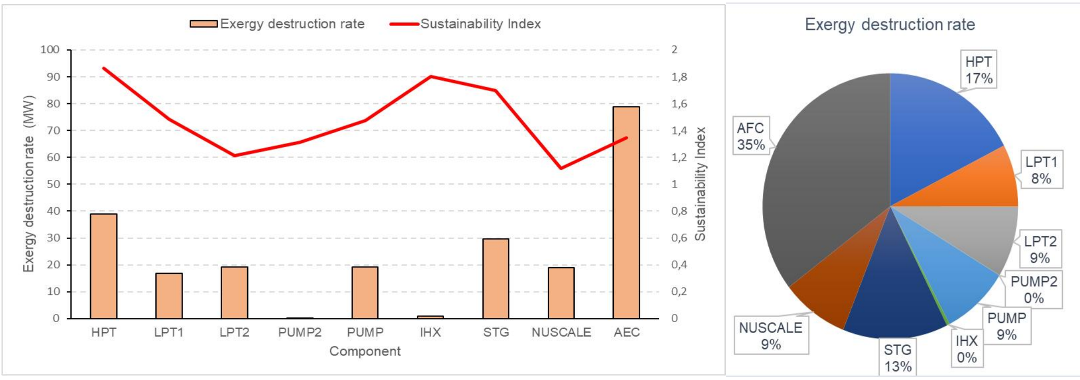
Fig. 4. Exergetic efficiency by flow diagram component.

We determined the exergy destruction rates of the main components of the flow diagram in addition to the sustainability index, as shown in Fig. 5. The sustainability index (SI) [18] for the main components is computed using the expression:

$$SI = \frac{1}{1-\varphi} = \frac{1}{1-\dfrac{ex_{prod}}{ex_{heat}}} \quad [8]$$

Where ex_{prod} and ex_{heat} are the specific exergy of the products and the heat supplied to the component respectively.

In this case, the AFC electrolyzer accumulates the highest exergy destruction rate values (78.91 MW), followed by the turbine, the heat exchangers, and the NuScale power module. Fig. 6 shows the exergy destruction rates of the proposed model's components.



(a) (b)

Fig. 5. Process components exergetic destruction rates and sustainability indices (a) and exergy destruction rate ratios (b).

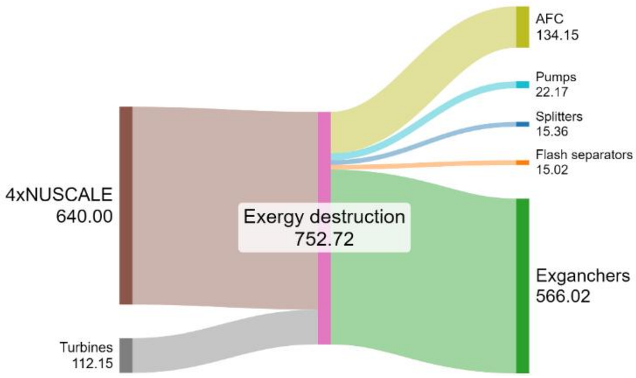


Fig. 6. Sankey diagram for the exergy destruction rate of the proposed model.

We evaluate the energy and exergy efficiency of the hydrogen production process by Huang and T-Raissi's (2005) definition as the ratio between the energy supplied to the process and the energy contained in the hydrogen produced [19]. An energy balance is applied to calculate the amount of the thermal and electrical energies supplied to the process, using the energy present in the hydrogen produced $LHV_{H_2} = 119,96 MJ/kg$ and the mass flux of hydrogen produced $\dot{m}_{H_2} = 0,4606 kg/s$. Therefore, we estimate the energy efficiency of the alkaline electrolysis process by:

$$\eta_{AFC} = \frac{\dot{m}_{H_2} LHV_{H_2}}{W_{AFC} + \left(S15 + S21 + S17 + S44 + S35\right)} = 0,1826$$

$$\psi_{AFC} = \frac{\dot{m}_{H_2} ex_{H_2}}{W_{AFC} + \left(S15 + S21 + S17 + S44 + S35\right)} = 0,3595$$

[9] [10]

We performed a global energy balance to estimate the overall process efficiency, employing the following expressions:

$$\eta_{overall} = \frac{\dot{m}_{H_2} LHV_{H_2} + W_{GT} - W_{pump} - W_{AFC}}{4 \times (\dot{m}_2 h_2 - \dot{m}_1 h_1)} = 0,2908 \quad [11]$$

$$\psi_{overall} = \frac{\dot{m}_{H_2} LHV_{H_2} + W_{GT} - W_{pump} - W_{AFC}}{4 \times (\dot{m}_2 ex_2 - \dot{m}_1 ex_1)} = 0,6109 \quad [12]$$

The energy and exergy efficiency values obtained for the complete model are suitable for implementation in the hydrogen economy, as they fall within the range typically reported for this type of technology. Tab. 2 displays the main results from the current model and the Gonzalez et al. (2019).

Tab. 2 –Hydrogen production process comparison between this proposal and González et al. (2019) reference design.

Parameter	**This proposal**	**Gonzalez et al (2019)**[17]
Overall hydrogen production rate (kg/s)	0,4606	0,2190
Temperature of hydrogen Produced (°C)	65,2	25
Pressure of the hydrogen produced (kPa)	395	101,3
Net thermal energy (MWth)	640	500
Net power produced (MWe)	198,09	292
System overall energy efficiency	0,2908	0,3247
System overall exergy efficiency	0,6109	0,5220
System overall exergy destruction rate (MW)	752,72	530,07
Hydrogen production process energy efficiency	0,1826	0,4533
Hydrogen production process exergy efficiency	0,3595	0,7622
Power conversion cycle energy efficiency	0,3296	0,4353
Power conversion cycle exergy efficiency	0,8143	0,7622

Meanwhile, the reference article implements a cogeneration seawater desalination system using the waste heat from the Cu-Cl thermochemical cycle. Therefore, the overall process efficiencies for this cogeneration process are inherently higher [20].

4. CONCLUSÃO

We present a comparative study of two hydrogen production processes using small modular nuclear reactor (SMR) designs as an energy source. In this proposal, a CPS model is developed to analyze the AFC alkaline electrolysis process coupled to four 160MWth NuScale power module designs. A cogeneration integration is proposed, using the heat from the process to heat the water flow before it enters the electrolyzer. Part of the energy generated in the Rankine cycle is dedicated to the electrolysis process, mainly for the AEC alkaline electrolyzer.

The energy and exergy efficiencies for the power conversion cycle are 32.96% and 81.43%, respectively. The Rankine cycle for the 4x160MWth project produces 264.14MWe with 198.09MWe injected into the electricity grid and the remaining 66.03MWe in the hydrogen production process. The AEC-type electrolyzer was sized with 42 stacks of 200 cells each for an LHV efficiency of 0.837 for this amount of energy available. This hydrogen production process produces 0.4606 kg/s of H_2 with energy and exergy efficiencies of 18.26% and 35.95%, respectively, for the electrolysis process. The exergy destruction rates of the main components of the flow diagram of the complete model, identifying the highest values in the AEC electrolyzer. Finally, we determined the overall efficiency of the NuScale-AEC integrated system to be 29.08% and 61.09%.

The results of this paper show greater hydrogen production capacity but with much lower efficiencies when compared to the results presented by González et al. (2019). Another relevant aspect is the amount of electricity available to the grid, which is considerably lower than the HTR-PM project, even with the higher thermal power of the SMRs. This proposal has an advantage over the Cu-Cl-HTR-PM project in terms of the pressure of the hydrogen produced, which reduces the subsequent costs of compressing it for storage.

It is important to note that although this proposal shows lower efficiency values compared to the HTR-PM project, it still demonstrates technically viable energy and exergy efficiencies for practical implementation. Moreover, the hydrogen production rate achieved by the alkaline electrolysis (AEC) system is comparable to values reported in the scientific literature. The sustainability index derived from the process flow diagram further supports the technical feasibility of this design, as it remains below the recommended threshold of two [18]. The choice of technology or another would be conditioned, for example, by criteria specific to the energy scenario in question and economic and social aspects.

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List of Acronyms and Symbols

SMR	Small Modular Reactor	CPS	Chemical Process Simulator
IHX	Intermediate Heat Exchanger	LHV	Low Heating Value
AEC	Alkaline Electrolyzer Cell	$\dot{m}$	Mass flow rate
COND	Condenser	η	Thermal efficiency
HPT	High-pressure turbine	ψ	Exergy efficiency
LPT	Low-pressure turbine	ex_X	Specific exergy of stream X
STG	Steam generator	W	Work
h_X	Specific enthalpy of stream X	Q	Heat