SOLAR ENERGY FOR SUSTAINABLE FUEL: A SELF-SUSTAINABLE BRAZILIAN LABORATORY FOR GREEN HYDROGEN AND AMMONIA

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Abstract

This paper presents the design, implementation, and safety framework of a self-sustainable green hydrogen and ammonia laboratory located in Florianópolis, southern Brazil (27°25'50.2"S, 48°26'27.7"W). The facility is primarily powered by photovoltaic (PV) energy and supported by a battery energy storage system (BESS), including second-life lithium-ion batteries, within a multifunctional building that integrates rainwater harvesting for electrolysis. The laboratory combines anion exchange membrane electrolysers with a pilot-scale Haber–Bosch ammonia synthesis unit to produce renewable hydrogen and ammonium-based fertilizers for agrivoltaic research. Beyond infrastructure description, the study analyzes the operational performance of photovoltaic-driven hydrogen production under real operating conditions. Dynamic PV–electrolyser coupling, control strategies to mitigate power fluctuations, and the impact of battery storage on system stability and annual operating hours are evaluated. Results show that while direct PV coupling maximizes instantaneous renewable energy use, battery integration significantly improves operational continuity by increasing electrolyser full-load hours. The laboratory serves as a replicable reference for integrated solar-to-hydrogen and solar-to-ammonia systems in Brazil and similar contexts.

Keywords: Green Hydrogen, Green Ammonia, Electrolysis, Haber-Bosch Process, BIPV.

1. Introduction

The transition to climate-neutral energy systems is fundamentally based on the use of renewable energy sources. However, these sources are often geographically and temporally mismatched with global energy demand. Hydrogen has emerged as one of the most promising energy carriers to address these challenges (Hossain Bhuiyan & Siddique, 2025). Due to its versatility, hydrogen can be combusted in engines and furnaces without generating greenhouse gas emissions or used in fuel cells to produce electricity, emitting only heat and water. Its potential to decarbonize sectors that are otherwise difficult to electrify, such as heavy industry, transport, and seasonal energy storage, makes hydrogen a key pillar in the global energy transition (Gomonov et al., 2025).

Brazil holds significant potential for green hydrogen production due to its abundant renewable energy resources, particularly hydro, solar, and wind power. The country's vast territory and high solar irradiance enable large-scale, low-cost hydrogen generation (Gurlit et al., 2021). Additionally, Brazil's existing infrastructure for energy exports and its growing industrial demand position it as a key player in the emerging global hydrogen economy. Strategic investments could strengthen their role as both a domestic supplier and international exporter of green hydrogen. Furthermore, converting green hydrogen into green ammonia offers a sustainable pathway to reduce the carbon footprint of Brazil's large agricultural sector, which is heavily reliant on nitrogen-based fertilizers (Teixeira et al., 2025).

While the global interest in green hydrogen is growing rapidly, real-world deployment still depends on integrated experimental platforms that can validate technologies under operational conditions, especially in tropical or developing country contexts. In this regard, universities and research centers play a critical role in bridging the gap between laboratory-scale innovation and scalable infrastructure. Pilot laboratories that combine renewable energy generation, energy storage, electrolysis, and chemical synthesis—within a safe and monitored environment—are essential to test technologies, assess performance, train human resources, and guide policy decisions (Harrison et al., 2023).

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Within this context, the Federal University of Santa Catarina (UFSC) established a multifunctional, self-sustainable laboratory designed to investigate and demonstrate the technical, operational, and safety aspects of green hydrogen and ammonia production powered by solar energy. The facility integrates photovoltaics, battery energy storage systems (including second-life batteries), rainwater harvesting, electrolysis, and a Haber-Bosch synthesis unit—offering a unique testbed for decarbonization strategies in Brazil and beyond (Walter et al., 2024).

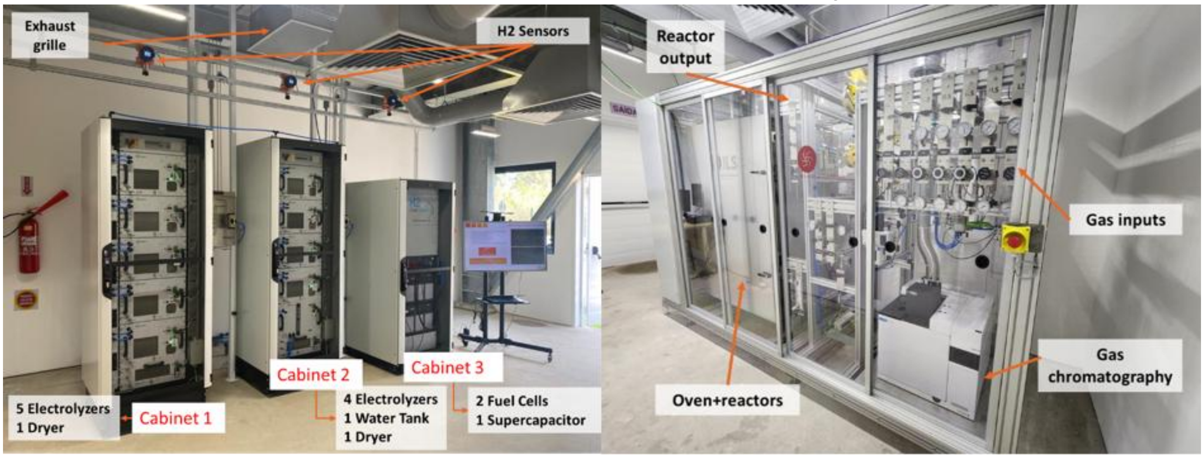
The objective of this paper is to describe this installation and the safety measures adopted on this self-sustainable laboratory at Florianópolis, in the south of Brazil (27°25'50.2"S 48°26'27.7"W), for the production of green hydrogen and green ammonia. In addition, the paper analyses the coupling between PV generation, battery energy storage systems, and electrolysis, assessing power availability, control strategies, and their impact on hydrogen production stability and annual operating hours.

2. Green Hydrogen Lab

The green hydrogen laboratory at the Solar Energy Research Laboratory Fotovoltaica/UFSC in Florianópolis, Brazil (27°S 48°W), presented in Figures 1 and 2, is designed to study hydrogen production from PV with battery storage to optimize future systems. It serves as a proof of concept for the technical and operational feasibility of solar-to-hydrogen systems in Brazil, supporting both academic research and real-world energy transition strategies.

The laboratory building exemplifies a multifunctional architectural approach, in which the PV rooftop structure not only serves as a source of renewable energy generation but also provides physical shelter and facilitates rainwater harvesting. Similarly, the PV façades contribute to electricity generation while functioning as sealing and shading elements, thereby enhancing indoor environmental comfort and reducing the reliance on artificial lighting and air conditioning systems. The rainwater harvested on the rooftops is filtered and used in the electrolysis process, enabling a fully renewable hydrogen production cycle. Therefore, in this integrated system, both solar energy and water are collected within the same building for hydrogen production. The total power integrated in the building sums up to 188 kWp (Pauli Custódio et al., 2025). The power is converted to AC and fed into the laboratory's power management system. To enable long-term experiments independent of solar radiation, additional power can be drawn from the grid. A Battery Energy Storage System (BESS) with two 100 kWh packs - one with new Li-ion batteries, the other with second-life batteries - allow for energy buffering and investigation of second-life battery performance and degradation (Zago Cantú et al., 2022). The power management system decides whether the energy supply should be provided from the PV system, batteries, or grid to an AEM electrolyser bank, which produces hydrogen from renewable energy as shown in Figure 3.

Figure 1: Green Hydrogen Laboratory at the Fotovoltaica/UFSC in Florianópolis, south of Brazil.



(a) **(b)**

Figure 21: AEM electrolysers (a) and Haber-Bosch ammonia synthesis reactor (b) at the Green Hydrogen Laboratory at the Fotovoltaica/UFSC in Florianópolis, south of Brazil.

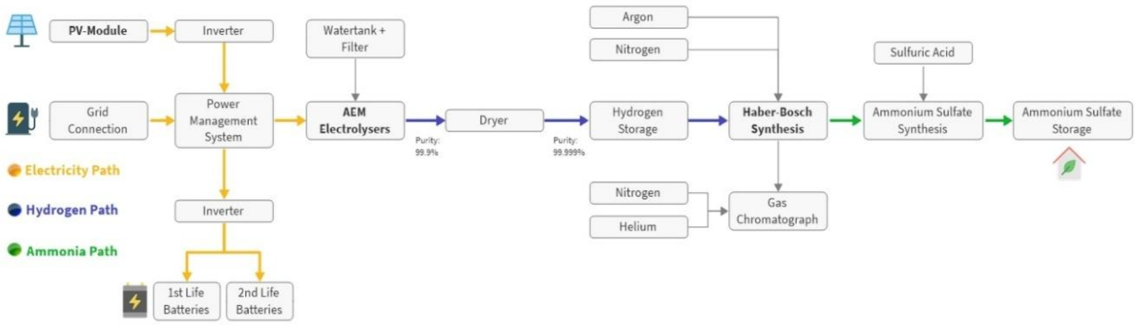


Figure 2: Schematic structure of the laboratory showing the paths of electricity, hydrogen and ammonia.

The electrolysis system (Figure 2a) employs AEM EL2.1 electrolysers from Enapter® (Enapter, 2020), each with an operative power consumption of 2400 W and a production rate of up to 500 NL/h at 99.9% purity. A total of nine EL2.1 units are installed at Fotovoltaica/UFSC. To enhance hydrogen purity, two Enapter DRY2.1 dryers (Enapter, 2020) were integrated, achieving a molar purity of 99.999% with an operative power consumption of 200 W. The purified hydrogen is compressed and stored in pressurized tanks for up to 300 bar. Currently, hydrogen is used for two main applications: (1) direct use in two 2 kW fuel cells and (2) ammonia synthesis via the Haber-Bosch process, followed by reaction with sulfuric acid to produce ammonium sulfate, intended as fertilizer for the laboratory's agrivoltaics (AgriPV) project (show in the upper right corner of Figure 1).

The laboratory also functions as a real-world testbed for data-driven modeling, energy systems education, and simulation validation. The lessons learned are expected to inform the development of similar solar-hydrogen infrastructures in other regions of Brazil, particularly in rural or isolated contexts. The facility is also integrated with electric mobility and second-life battery research, expanding its contribution to cross-sectoral decarbonization strategies.

3. Green Ammonia Lab

In September 2023, the laboratory received an Ammonia Synthesis Unit (Figure 2b) designed by ILS Integrated Lab Solutions GmbH. It uses the Haber-Bosch process to convert hydrogen and nitrogen to ammonia, serving as a research platform. The skid consists of two reactors, directional valves and pressure regulators, and a custom-made Gas Chromatograph (Agilent 8860), in short GC, for analysis (provided by Joint Analytical Systems GmbH, JAS). The reactors are filled with an iron oxide-based catalyst. System operation and data acquisition are managed via dedicated software platforms for both the synthesis and analysis of subsystems.

Operators can define the composition of the syngas, including reference gases such as argon to regulate internal flow. Helium is used as the carrier gas in the gas chromatograph. The syngas enters the reactor chamber, which is equipped with multiple safety mechanisms to mitigate overpressure risks. The gas flow configuration for hydrogen, nitrogen, and carrier gases is shown in Figure 4.

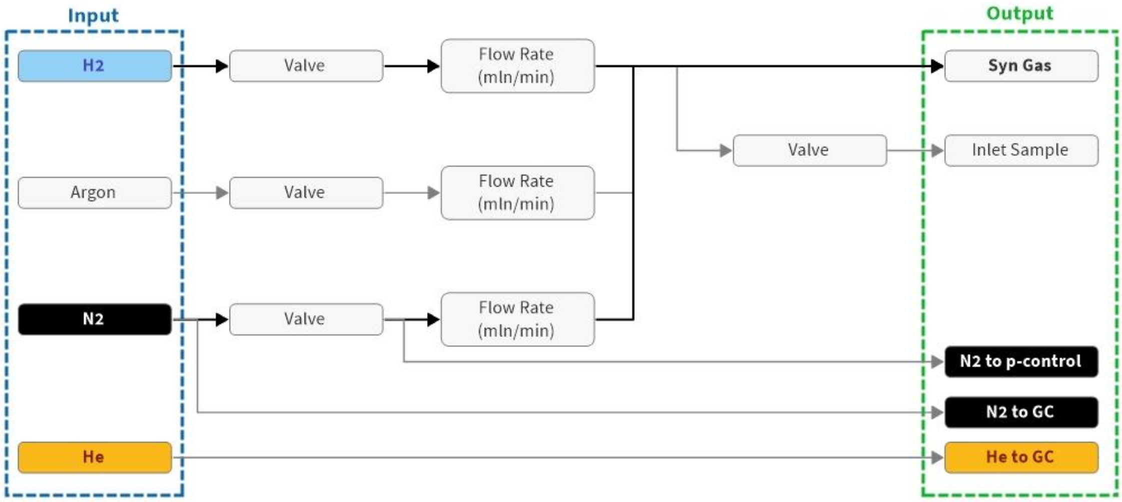


Figure 4: Schematic diagram of the gas flow and control system used for ammonia synthesis experiments.

The two reactors can operate in series or independently, with Reactor 2 optionally bypassed. Temperatures are controlled in three separate heating zones on both the outer and inner sections of the reactors. Gas samples are collected at three points—(1) before reaction (Inlet Sample), (2) between reactors (Inter Sample), and (3) after Reactor 2 (Product Sample)—and analyzed in the GC to monitor gas composition and process efficiency. The process flow and reactor configuration are illustrated in Figure 5.

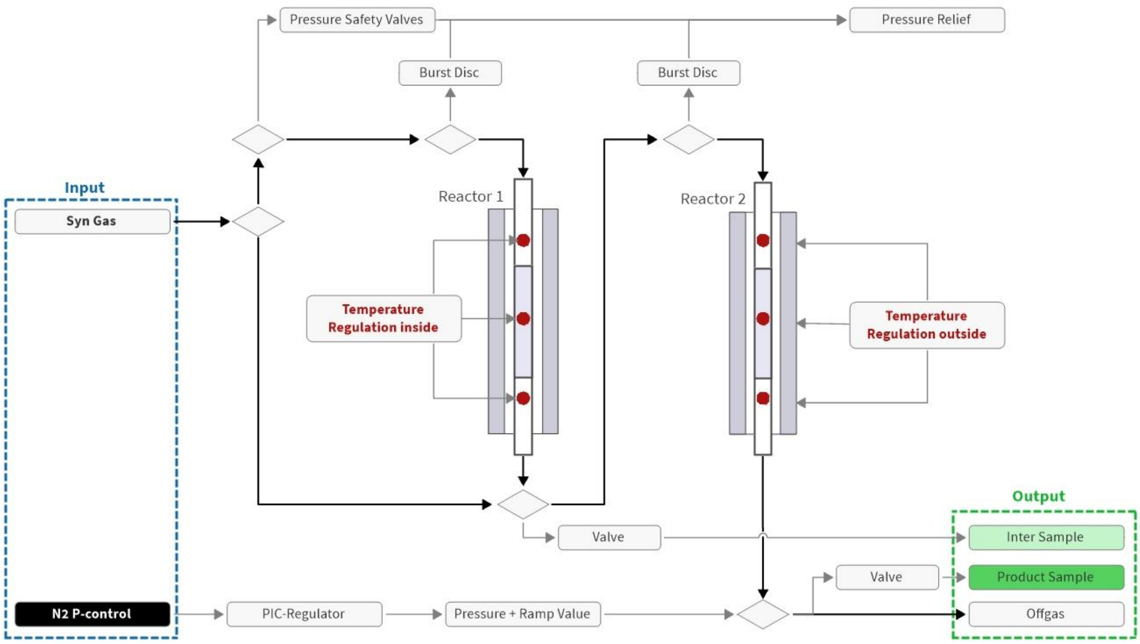


Figure 5: Process flow diagram of the ammonia synthesis reactors showing pressure and temperature control systems.

The produced ammonia is subsequently reacted with sulfuric acid to obtain ammonium sulfate, which is used as a fertilizer in the laboratory's AgriPV research initiative.

4. Safety Measures

The safety strategy of the Green Hydrogen and Ammonia Laboratory was developed through a comprehensive risk assessment addressing hydrogen production, high-pressure storage, and chemical synthesis operations. The resulting concept integrates multiple layers of protection—encompassing structural design, automated systems, and procedural protocols—to ensure secure and continuous operation. This safety plan was developed in collaboration with the local Fire Department, ensuring compliance with emergency regulations and best practices for handling flammable gases and pressurized systems.

The laboratory building itself incorporates passive safety features, including fire-resistant walls and doors rated for 120 minutes, which provide a crucial buffer in case of combustion-related incidents. In the hydrogen production area, a high-capacity forced ventilation system (500 m³/h) ensures continuous air exchange to avoid gas accumulation. Hydrogen and ammonia gas detectors are installed at key points and integrated into a centralized safety control system (Figure 6).

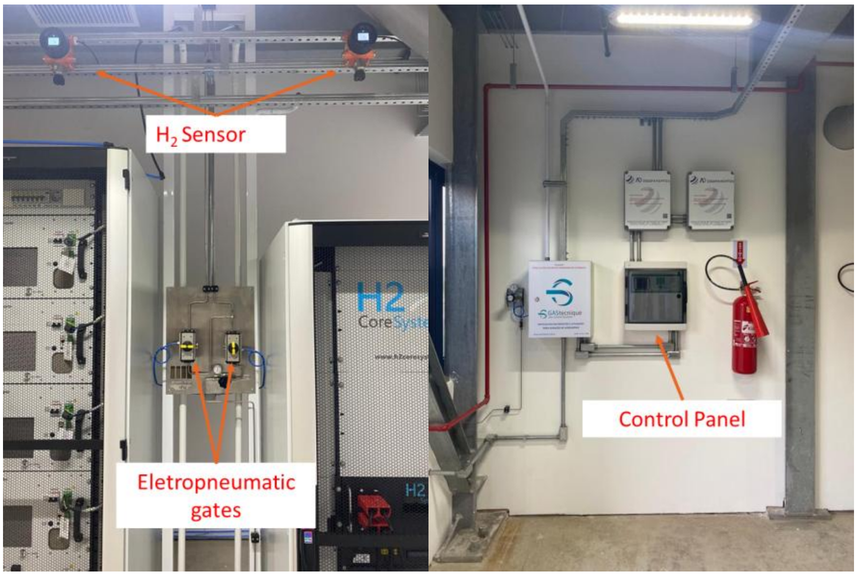


Figure 6: Safety elements in the H2 room.

In the event of a gas leak, the detection system activates pneumatic valves that automatically seal the pipelines and inject argon gas into the circuit to inert any residual hydrogen, mitigating the risk of ignition. These active protections allow for rapid containment and neutralization of hazardous situations.

The ammonia synthesis unit includes redundant overpressure protections, burst discs, and multi-zone temperature controls. All critical operations are monitored in real time through dedicated software that manages alarms and automated shutdowns in case of unsafe deviations.

All technical gases used in the facility—including hydrogen, argon, helium, and nitrogen—are stored in a dedicated, ventilated gas storage housing located outside the main laboratory. This structure was designed to isolate flammable materials from the main building while allowing for proper ventilation and external monitoring (Figure 7).

Figure 7: External storage gas housing for hydrogen (left image) and other gases.

Altogether, the laboratory's safety architecture reflects a robust and integrated approach, combining structural resilience, automated emergency responses, and regulatory alignment to support safe research in hydrogen and ammonia technologies.

5. Analysis of Green Hydrogen Production

This section evaluates the operational performance of photovoltaic-driven hydrogen production at the Fotovoltaica/UFSC laboratory under real operating conditions. The inherent intermittency of solar generation challenges stable electrolyser operation, particularly for AEM technologies sensitive to frequent start–stop cycles. The analysis focuses on the coupling between PV generation, battery energy storage, and electrolysis, assessing power availability, control strategies, and their impact on operating hours and system stability.

The hydrogen production system requires an energy-intensive warm-up phase at each start-up (Walter et al., 2024). It is therefore crucial to minimize the number of on/off cycles. Since solar energy is intermittent and highly variable at very short timesteps, real-time control of hydrogen production is particularly challenging.

Different power thresholds were defined to represent the available PV energy relative to the electrolyser's nominal capacity:

- ≥ 100 %: sufficient power to operate at full capacity (≈ 25 kW, corresponding to up to 500 NL/h);
- 80 – 100 %: partial load operation at reduced power;
- 60 – 80 %: minimum threshold for stable operation (≈ 300 NL/h).

Figure 8 illustrates a representative day of photovoltaic electricity generation from the building-integrated façade systems of the laboratory (June 24, 2025), based on real operational data. Using this measured PV production profile, the figure also illustrates how a dynamic coupling strategy would operate, in which the 25 kW electrolyser continuously adjusts its power setpoint to follow the instantaneous availability of solar energy. This approach allows the system to maximize direct utilization of photovoltaic generation by converting surplus electricity into hydrogen whenever sufficient power is available.

As shown in Figure 8, the PV power output exhibits pronounced short-term fluctuations throughout the day, mainly driven by transient cloud cover. Under dynamic coupling, these rapid variations are directly transferred to the electrolyser, forcing operation under highly variable partial-load conditions at the time resolution considered. Such behavior increases control complexity and may compromise operational stability, particularly for AEM electrolysers, which are sensitive to frequent power changes and repeated transitions between operating regimes. Consequently, although dynamic coupling maximizes renewable energy use on an instantaneous basis, it may lead to reduced efficiency and accelerated degradation if not complemented by appropriate control strategies or energy buffering solutions.

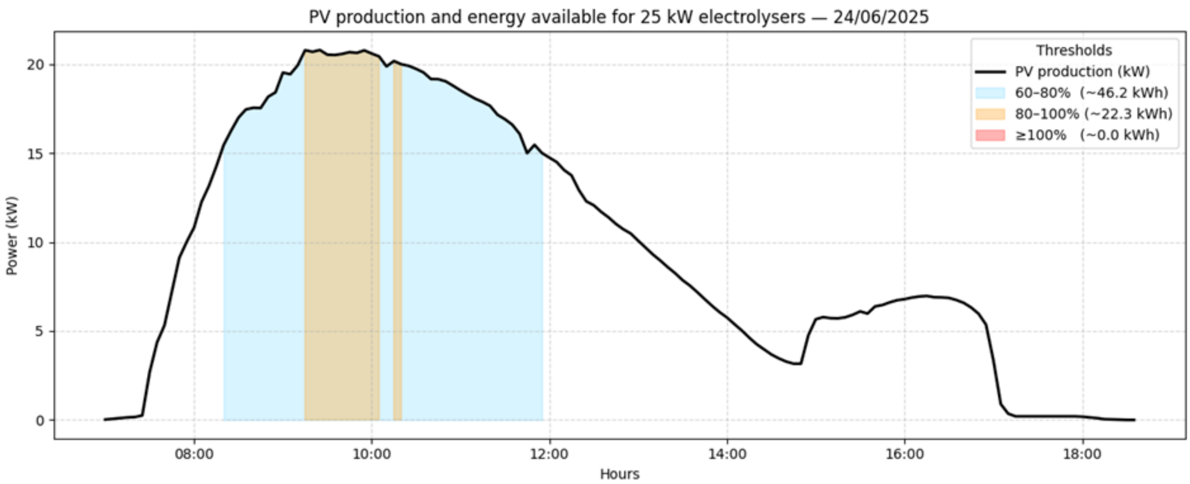


Figure 8: Real-time coupling between PV production and electrolyser operation for June 24, 2025. The electrolyser adjusts its power according to the instantaneous PV output from façade systems.

Annual operating hours for different nominal electrolyser capacities (25–100 kW) were subsequently estimated based on PVsyst simulations considering the complete building-integrated photovoltaic (BIPV) installation, including both rooftop and façade systems (Figure 9). The results indicate that for a substantial portion of the year, the available photovoltaic power exceeds the nominal capacity of the hydrogen production system. In the absence of energy storage, this surplus electricity cannot be directly converted into hydrogen and is therefore underutilized.

Increasing the nominal capacity of the hydrogen production system could improve direct utilization of photovoltaic energy; however, oversizing the electrolyser may result in extended operation under partial-load conditions, potentially reducing efficiency and increasing component degradation. This trade-off highlights the limitation of relying solely on electrolyser sizing to accommodate PV variability. Consequently, the integration of battery energy storage systems emerges as a more effective strategy to absorb excess photovoltaic generation and support stable hydrogen production without excessive oversizing of the electrolysis unit.

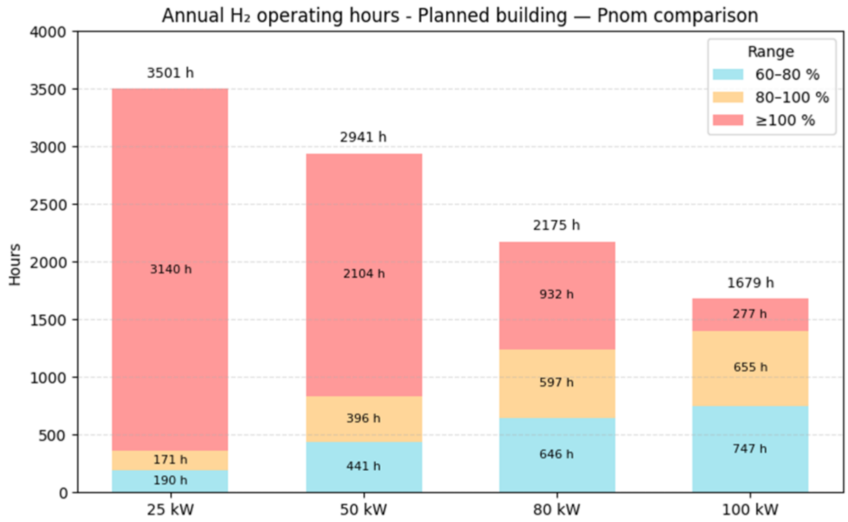


Figure 9: Annual operating hours of the AEM electrolyser for different nominal powers (25–100 kW), based on PVsyst simulation production data for the complete BIPV system.

To mitigate frequent start–stop events and rapid power fluctuations, a two-level control strategy was implemented for the electrolyser operation. Under this strategy, when the available photovoltaic power is sufficient to sustain at least 60% of the nominal capacity, the system operates continuously at this partial-load level. As PV availability increases and reaches the full nominal threshold, the electrolyser transitions to full-load operation (25 kW). Conversely, when PV power decreases below the 100% threshold, the system returns to the 60% operating mode rather than shutting down completely (Figure 10).

By preventing unnecessary on/off transitions, this control approach significantly reduces thermal cycling and avoids repeated warm-up phases, which are known to negatively affect electrolyser durability. As a result, the strategy contributes to improved operational stability and extended electrolyser lifetime, particularly for AEM technologies sensitive to frequent load variations.

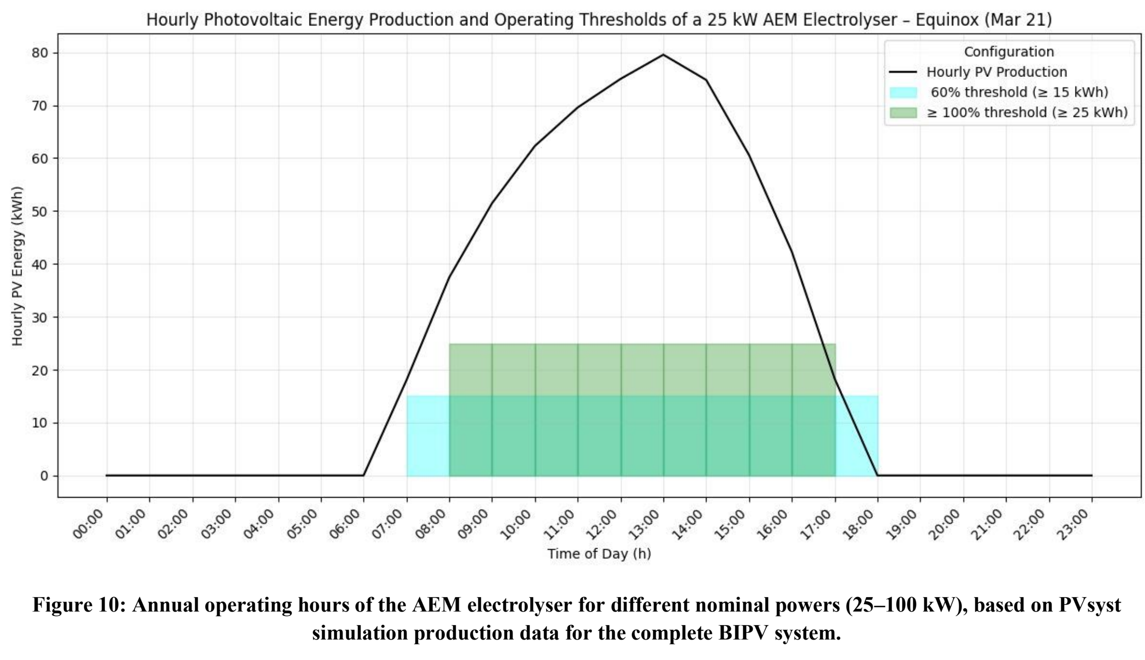


Figure 10: Annual operating hours of the AEM electrolyser for different nominal powers (25–100 kW), based on PVsyst simulation production data for the complete BIPV system.

Another analysis performed in this study investigates the impact of integrating a battery energy storage system into the photovoltaic-driven hydrogen production scheme. In this configuration, surplus photovoltaic energy that cannot be directly utilized under dynamic coupling conditions is stored in battery systems, comprising both new lithium-ion batteries and second-life battery packs. The stored energy is subsequently used to sustain hydrogen production during periods of low or zero solar generation, such as early morning, late afternoon, and nighttime operation. By extending the continuous operating phase of the electrolyser, this approach substantially increases the total annual operating time of the hydrogen production system.

As shown in Figure 11, the incorporation of battery storage results in a significant increase in annual full-load hours (FLH), from 3426 h under direct PV coupling to 7566 h in the storage-assisted configuration. These results highlight the critical role of energy buffering in mitigating photovoltaic intermittency, enhancing operational stability, and maximizing the utilization of renewable energy for hydrogen production.

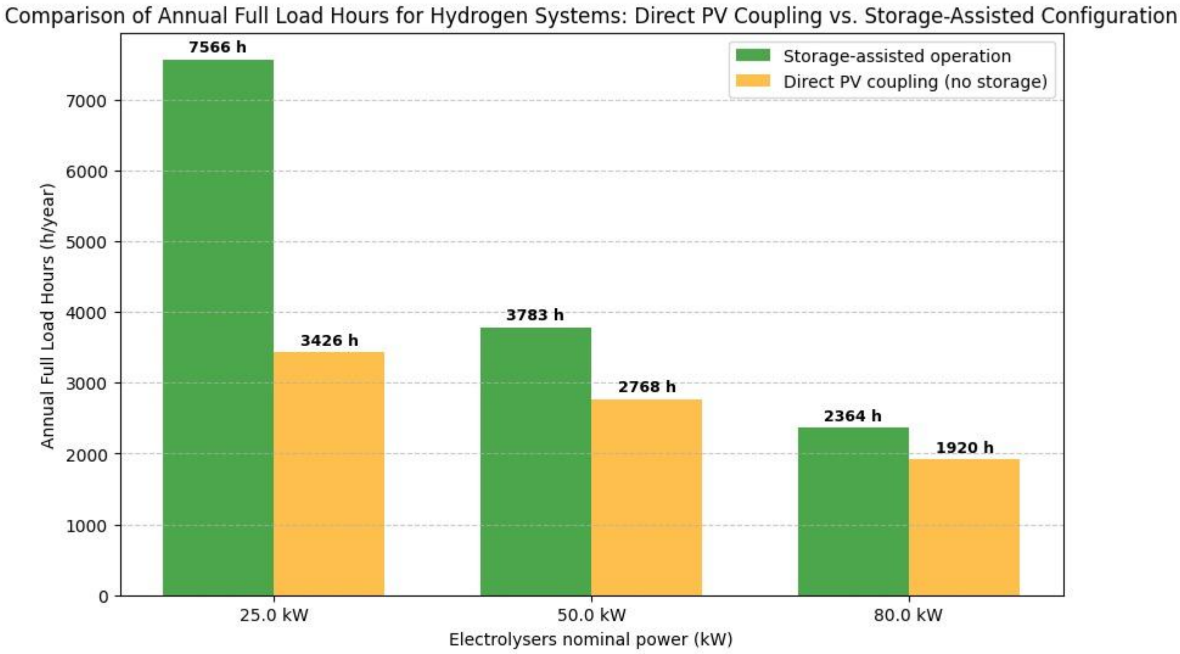


Figure 11: Annual full load hours (FLH) for hydrogen production under two operation modes: direct PV coupling (yellow) and storage-assisted configuration (green).

For larger-scale or industrial applications, where continuous operation and process stability are essential, the results indicate that higher energy storage capacities and more conservative operational margins would be required to compensate for photovoltaic variability and ensure a reliable hydrogen supply.

7. Conclusion

This work presented the development, implementation, and operational assessment of a self-sustainable green hydrogen and ammonia laboratory powered primarily by photovoltaic generation and supported by battery energy storage. The results demonstrate that establishing this type of infrastructure in Brazil is not only feasible but essential for advancing national technological autonomy in emerging hydrogen industries. By enabling real-world testing, workforce development, and optimization of integrated energy systems, the laboratory represents a strategic milestone toward the creation of a domestic value chain for green hydrogen and green ammonia production.

A key outcome of this demonstration is the successful integration of robust safety systems capable of supporting hydrogen production and high-pressure storage within a multifunctional building environment. The automated shutdown mechanisms, gas leak detection, fire-resistant structural segmentation, and inertization strategies adopted here provide a solid technical basis for future deployments in research, industrial, or urban settings.

From the energy system perspective, the operational analysis confirmed the critical importance of energy storage. While direct photovoltaic coupling results in limited stability and reduced full-load operation, the incorporation of BESS significantly increases annual full-load hours of the 25 kW electrolyser, maximizing renewable utilization and minimizing thermal cycling. Therefore, storage integration stands as a fundamental requirement for reliable and efficient hydrogen production in variable solar conditions.

This facility operates as a replicable reference for future hydrogen deployments in Brazil, supporting the country's trajectory toward a competitive, low-carbon energy economy. Future work will focus on upscaling production, enhancing system automation, advancing second-life battery evaluation, and improving ammonia synthesis efficiency using fully renewable energy inputs.

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