Operational Modeling of Green Hydrogen Production in Sugarcane Biorefineries Considering Electricity Price Variability

Julia Bahia Hufnagel Cavalcante[1]*, Fernando Luiz Pellegrini Pessoa[2]
[1]SENAI CIMATEC University, Postgraduate Program in Computational Modeling and Industrial Technology; [2]SENAI CIMATEC University, Chemical Department; Salvador, Bahia, Brazil

This study evaluates green hydrogen production from surplus electricity in sugarcane biorefineries, considering partial electrolyzer operation as a function of electricity price. A techno-economic model was developed to estimate the Levelized Cost of Hydrogen (LCOH) under different electricity price scenarios. The results indicate that electricity cost is the main driver of LCOH, accounting for approximately 45% of total annual cost under low-price conditions and reaching values close to 80% in high-price scenarios. Distinct operational regimes were identified, with full electrolyzer utilization at low electricity prices (0.04–0.06 R$/kWh), resulting in LCOH between 10.7 and 11.8 R$/kg, and reduced operation at higher prices, leading to a sharp increase in costs. A critical electricity price range between 0.10 and 0.16 R$/kWh was identified, above which the economic viability of green hydrogen deteriorates significantly. Although competitive with values reported in the literature for green hydrogen, the results indicate limited competitiveness compared to grey hydrogen and closer proximity to blue hydrogen costs under favorable conditions. Overall, the findings highlight the potential of the Brazilian sugarcane sector for decentralized green hydrogen production under low-cost electricity conditions.
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The growing concern about climate change and the need to reduce greenhouse gas emissions have driven the search for energy sources that are both economically viable and environmentally sustainable. In this context, green hydrogen (GH_2) has emerged as a strategic energy carrier for the decarbonization of sectors such as heavy industry and transportation [1]. According to the International Energy Agency (IEA), low-emission hydrogen production grew by 10% in 2024, but still accounts for less than 1% of total global production, being limited by high capital costs, regulatory uncertainties, and infrastructure challenges [2].

In Brazil, the scenario may be more favorable for green hydrogen production due to the high share of renewable sources in the electricity mix, which exceeds 88% of total generation. This expansion of renewable sources may lead to the occurrence of surplus electricity, creating opportunities for its use in hydrogen production via electrolysis and contributing to lower electricity costs [3,4]. Brazilian sugarcane biorefineries emerge as a promising opportunity in this context. In addition to producing sugar and ethanol, these facilities use bagasse and straw to generate energy through cogeneration, often producing significant electricity surpluses per production unit. In 2025, sugarcane biomass accounted for approximately 12,697 MW of installed cogeneration capacity, representing about 71.9% of the total biomass-based capacity in Brazil [5,6]. However, most studies in the literature consider electrolyzer operation coupled with wind or solar energy, which can be modeled based on hourly electricity prices. This approach does not adequately represent the operational reality of industrial cogeneration systems based on renewable energy, such as sugarcane biorefineries. In this sense, the integration of these facilities with electrolysis systems emerges as a promising alternative for green hydrogen production [7].

In this context, this study aims to propose a model to evaluate green hydrogen production from surplus energy in sugarcane biorefineries, considering electrolyzer operation as a function of electricity prices.

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Address for correspondence: Julia Bahia Hufnagel Cavalcante. Av. Orlando Gomes, 1845 - Piatã, Salvador – BA – Brazil, Zipcode: 41650-010. E-mail: julia.cavalcante@aln.senaicimatec.edu.br.

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Materials and Methods

This study adopts a techno-economic modeling approach to evaluate green hydrogen (GH_2) production from surplus electricity in sugarcane biorefineries, considering the operation of the electrolyzer as a function of electricity prices in the Brazilian short-term (spot) market.

A high-efficiency sugarcane biorefinery was considered as a case study, with an annual electricity surplus of 377 GWh. The electrolyzer capacity was sized based on the available energy, assuming an average annual operation of 5,500 hours during the harvest season in Brazil, resulting in an installed capacity of 68.5 MW [8,9].

Proton Exchange Membrane (PEM) electrolysis was selected as the hydrogen production technology due to its balance between technological maturity, operational flexibility, and the high purity of the hydrogen produced. The specific energy consumption of the electrolyzer was assumed to be 53 kWh/kg, based on values reported in the literature [10–13].

Although the electricity used in the electrolysis process is derived from the surplus generated by the biorefinery itself, an opportunity cost was assigned to this energy, since it could alternatively be sold in the spot electricity market. Therefore, by allocating surplus electricity to hydrogen production, the plant foregoes potential revenue from electricity sales.

The operation of the electrolyzer was modeled as a function of electricity price (Equation 1), representing the economic decision regarding the use of surplus energy (0–100%). At low electricity prices, the entire surplus generated by the plant is directed to hydrogen production rather than being sold in the spot market. Conversely, at higher electricity prices, the electrolyzer operates at a minimum level, ensuring that capital investment is not underutilized while prioritizing electricity sales.

$$f(P) = \begin{cases} 1, & P \leq P_{low} \\ f_{min} + (1 - f_{min}) \cdot \frac{P_{high} - P}{P_{high} - P_{low}}, & P_{low} < P < P_{high} \\ f_{min}, & P \geq P_{high} \end{cases} \quad (1)$$

Where P is the electricity price in the spot market, f_{min} is the minimum fraction of surplus energy used for hydrogen production (20%), P_{low} = 0.06 R$/kWh and P_{high} = 0.58 R$/kWh, corresponding to real values observed between 2021 and 2026 in the Central-West/Southeast region of Brazil [14].

The specific cost of the electrolyzer was assumed to be 1100 $/kW, a value consistent with commercial PEM electrolysis systems, converted to Brazilian reais (exchange rate of 5.25 R$/US$ as of March 12, 2026) [12,13,15].

Costs related to water consumption, hydrogen compression, and storage were treated in a simplified manner as auxiliary system costs. According to the literature, these components represent a relatively small share of the total production cost and were incorporated as additional percentages in the model.

The OPEX for compression and storage was assumed to be 2% of the total CAPEX for each component. Based on literature data, the general operation and maintenance costs (OPEX) of the electrolysis system were assumed to be approximately 2% of the total CAPEX per year. Considering the additional OPEX associated with compression and storage, the total operational expenditure in the model corresponds to approximately 6% of the CAPEX on an annual basis [16].

The capital expenditure (CAPEX) was annualized using the capital recovery factor (CRF), considering a discount rate of 7% and a project lifetime of 20 years. The electricity cost was calculated based on the energy consumption and electricity prices ranging from 0.04 to 0.9 R$/kWh, in order to evaluate the model behavior [5].

The total annual cost was defined as the sum of the annualized CAPEX, OPEX, and electricity cost. The Levelized Cost of Hydrogen (LCOH) was then calculated as the ratio between the total annual cost and the annual hydrogen production.

Results and Discussions

The electricity price assumptions, as well as the corresponding LCOH results, are presented in Table 1.

Table 1. Model results.

Case	Price (R$/kWh)	f(P)	Energy used (GWh/year)	H_2 (t/year)	Electricity Cost (MR$/year)	Total Cost (MR$/year)	LCOH (R$/kg)
1	0.04	100%	377.7	7,127	15,110	76,350	10.71
2	0.06	100%	377.7	7,127	22,666	83,905	11.77
3	0.10	94%	354.5	6,689	35,451	96,691	14.46
4	0.16	85%	319.6	6,031	51,143	112,382	18.63
5	0.30	63%	238.3	4,495	71,484	132,723	29.52
6	0.40	48%	180.2	3,399	72,064	133,305	39.22
7	0.50	32%	122.1	2,303	61,023	122,262	53.09
8	0.58	20%	75.5	1,425	43,820	105,059	73.70
9	0.90	20%	75.5	1,425	67,997	129,236	90.66

The results indicate that electricity cost exerts a strong influence on the LCOH, accounting for approximately 45% of the total annual cost under low electricity price scenarios and reaching values close to 80% in high-price scenarios. More importantly, the results reveal the existence of distinct operational regimes directly linked to electricity price.

For low electricity prices (0.04–0.06 R$/kWh), the system operates at full capacity ($f \approx 1$), resulting in LCOH values between 10.7 and 11.8 R$/kg. In this regime, the high utilization of the electrolyzer allows for better dilution of capital costs, leading to more competitive hydrogen production. When compared to values reported in the literature for green hydrogen (R$ 15.1–18.7/kg), the results indicate that surplus-based systems can achieve competitive cost levels under favorable electricity conditions [17].

However, when compared to conventional hydrogen production routes, the competitiveness remains limited. Even under low electricity price scenarios, the LCOH remains above the cost range of grey hydrogen (R$ 2.6–8.9/kg), mainly due to the high capital cost of electrolyzers. On the other hand, the results show closer proximity to blue hydrogen costs (R$ 5.3–10.5/kg), particularly under low-cost electricity scenarios [13].

As electricity prices increase, the system enters a transition regime (0.10–0.16 R$/kWh), in which the utilization factor decreases (f between 0.94 and 0.85). In this range, the reduction in electrolyzer operation is not sufficient to offset the increase in electricity cost, resulting in a significant rise in LCOH (14.5–18.6 R$/kg). In this regime, green hydrogen becomes less competitive even when compared to other low-carbon alternatives.

For higher electricity prices (>0.30 R$/kWh), the electrolyzer operates at low capacity ($f \leq 0.63$), with a substantial reduction in hydrogen production and a sharp increase in LCOH, reaching values above 90 R$/kg. In this regime, electricity cost dominates the economic performance, making hydrogen production economically unattractive across all considered production pathways.

These results highlight that the economic viability of green hydrogen production in integrated systems is highly dependent on access to low-cost electricity, reinforcing the importance of operational flexibility in response to market conditions.

Conclusion

This study proposed a techno-economic model to evaluate green hydrogen production from surplus electricity in sugarcane biorefineries, integrating both the opportunity cost of electricity and the partial operation of the electrolyzer as a function of electricity price. Unlike conventional approaches, the proposed model provides a more realistic representation of operational decision-making by considering electricity not only as an input, but also as an economic alternative.

The results demonstrated that electricity cost exerts a strong influence on the LCOH, accounting for approximately 45% of the total annual cost under low-price scenarios and reaching values close to 80% under higher electricity price conditions. The identification of distinct operational regimes, as well as a critical electricity price range, highlights the model's consistency in capturing the economic behavior of the system under varying market conditions.

Furthermore, the model structure, based on technical and economic parameters widely reported in the literature, ensures robustness and allows its application across different scenarios and plant scales. This approach makes the model a useful tool for both academic analysis and decision-making support in real-world projects.

From an applied perspective, the results reinforce the potential of the Brazilian sugarcane sector as a platform for green hydrogen production, particularly due to the availability of surplus electricity and the well-established cogeneration infrastructure. The integration of electrolyzers into these facilities represents a concrete opportunity for revenue diversification, improved energy utilization, and reduced exposure to electricity market volatility.

Future work may further develop the model through sensitivity analysis to identify additional parameters that significantly influence the LCOH, alongside electricity price.

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