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HYDROGEN PRODUCTION PATHWAYS IN BRAZIL: A COMPARATIVE TECHNO-ECONOMIC AND POLICY ASSESSMENT OF ELECTROLYSIS AND ETHANOL STEAM REFORMING

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ABSTRACT

This article presents a comparative techno-economic and public policy assessment of the main hydrogen production pathways in Brazil: water electrolysis powered by renewable electricity and ethanol steam reforming. The country represents a unique case in the international energy landscape by combining a predominantly renewable electricity matrix with a mature and competitive bioenergy sector centered on sugarcane ethanol. The analysis adopts an engineering economics framework based on the Levelized Cost of Hydrogen (LCOH), decomposing capital costs, operating costs, energy inputs, and financial parameters. Sensitivity analyses are conducted for electricity and ethanol prices, capital costs, discount rates, and utilization factors, with the objective of translating technical assumptions into policy-relevant scenarios. The results indicate that ethanol steam reforming tends to exhibit lower costs in the short to medium term due to the high share of feedstock costs and lower capital intensity. Water electrolysis, in turn, becomes progressively competitive under scenarios of low-cost renewable electricity and declining electrolyzer CAPEX. The study concludes that a national strategy based on the coexistence of technological pathways, supported by coordinated regulatory instruments, can enhance the robustness and efficiency of Brazil's transition toward a hydrogen economy.

Keywords: Hydrogen. Electrolysis. Ethanol steam reforming. Engineering economics. Energy policy.

1. INTRODUCTION

The global commitment to climate neutrality has intensified efforts to identify low-carbon energy carriers capable of decoupling economic growth from greenhouse gas emissions. As energy systems undergo structural transformation, the limitations of fossil fuel–based technologies have become increasingly evident, particularly in sectors where direct electrification remains technically constrained or economically inefficient. In this context, hydrogen has emerged as a strategic energy carrier with the potential to support deep decarbonization across multiple segments of the economy.

Hydrogen's relevance stems from its role as a versatile secondary energy vector. It enables decarbonization in energy-intensive industrial processes—such as steelmaking, refining, and chemical production—while also offering solutions for heavy-duty transport, maritime applications, and long-duration energy storage. By converting electricity into a storable chemical form, hydrogen can enhance the flexibility of power systems with high shares of variable renewable generation, contributing to system stability and resilience.

The environmental and economic performance of hydrogen, however, depends critically on the production pathway employed. Currently, most hydrogen is produced via fossil-based steam methane reforming, a process associated with significant carbon dioxide emissions. This has driven growing interest in alternative routes that combine lower environmental impact with economic feasibility. Among these, water electrolysis powered by renewable electricity has gained prominence as the main pathway for green hydrogen. Despite its alignment with long-term decarbonization goals, large-scale deployment of electrolysis remains constrained by high capital costs, limited economies of scale, and strong sensitivity to electricity prices and utilization rates.

In parallel, hydrogen production through the steam reforming of renewable fuels—particularly ethanol derived from biomass—has emerged as a complementary pathway. Although this route involves direct CO_2 emissions at the point of production, its life-cycle carbon footprint can be substantially reduced when sustainably produced bioethanol is used. From a systems perspective, ethanol steam reforming benefits from greater technological maturity, lower capital intensity, and reduced exposure to electricity price volatility, making it particularly relevant in regions with established bioenergy infrastructures.

Brazil represents a distinctive case within this global landscape. The country combines a predominantly renewable electricity matrix with one of the world's most competitive and mature ethanol industries, creating favorable conditions for the coexistence of multiple hydrogen production pathways. In such a setting, technology choice cannot be reduced to a purely technical comparison but instead becomes a system-level optimization problem involving capital allocation, operating cost structures, energy prices, utilization rates, and policy design over time.

Despite a growing body of literature on hydrogen production technologies, important gaps remain regarding the interaction between policy design, market regulation, and the relative competitiveness of alternative hydrogen pathways. Most existing studies focus on a single production route or rely on static cost comparisons that abstract from electricity market rules, biofuel policies, and investment risk. As a result, the literature offers limited guidance on how hydrogen strategies should be sequenced and adapted in country-specific contexts such as Brazil, where renewable electricity and bioenergy coexist as strategic resources.

This article addresses these limitations by providing a comparative assessment of water electrolysis and ethanol steam reforming from an engineering economics perspective, explicitly embedding the analysis within a policy-oriented sensitivity framework. The study emphasizes CAPEX–OPEX trade-offs, the formation of the Levelized Cost of Hydrogen (LCOH), and the role of key regulatory instruments—such as power purchase agreements, grid access regulation, RenovaBio, and CBIO pricing—in shaping economic outcomes. By translating techno-economic sensitivities into coherent policy scenarios, the analysis provides decision-relevant insights for designing adaptive, risk-aware, and cost-efficient hydrogen strategies in Brazil.

1.1 GAPS IN EXISTING HYDROGEN COST ASSESSMENTS AND CONTRIBUTION OF THIS STUDY

Although the literature on hydrogen production has expanded rapidly, several gaps continue to motivate further research. First, most assessments focus on individual production pathways—predominantly water electrolysis—or rely on global and regional averages that inadequately capture country-specific energy structures. In particular, the coexistence of a highly renewable electricity system with a large-scale, mature bioenergy sector, as observed in Brazil, remains underexplored in comparative techno-economic analyses. Second, many studies adopt static cost comparisons that overlook financial parameters, utilization rates, and market design, thereby underestimating the role of policy and institutional arrangements in shaping hydrogen competitiveness. Third, the interaction between engineering economics and regulatory instruments—such as electricity market rules, biofuel pricing frameworks, and financing conditions—has not been sufficiently addressed within integrated analytical frameworks.

This study contributes to the literature by addressing these gaps through a comparative assessment of water electrolysis and ethanol steam reforming explicitly tailored to Brazilian conditions. By combining a detailed LCOH-based engineering economics framework with systematic sensitivity analysis, the article moves beyond single-point cost estimates and identifies conditional competitiveness domains linked to concrete policy choices. In doing so, it provides original insights into how alternative hydrogen pathways respond differently to electricity prices, feedstock costs, capital intensity, and financing structures. The Brazilian case thus serves not only as an empirical application, but also as a conceptual illustration of how heterogeneous energy endowments can be leveraged through differentiated hydrogen policy design.

2. METHODOLOGICAL FRAMEWORK

The comparative assessment is conducted within an engineering economics framework based on the Levelized Cost of Hydrogen (LCOH), which represents the discounted average cost of producing one kilogram of hydrogen over the lifetime of a production facility. The LCOH enables consistent comparison across hydrogen production pathways with distinct capital intensity, operating characteristics, and cost structures, including water electrolysis and ethanol steam reforming. This methodological structure provides the analytical basis for the cost ranges and competitiveness thresholds discussed in Section 4 (Results) and underpins the policy interpretation developed in Section 6 (Policy Discussion).

For each pathway, the LCOH is decomposed into capital expenditure (CAPEX), operating expenditure (OPEX), feedstock or energy input costs, and key financial parameters, notably the discount rate and plant lifetime. Rather than producing a single deterministic cost estimate, the analysis maps the economic space within which each hydrogen pathway becomes competitive under Brazilian conditions. This approach allows the identification of cost drivers and break-even conditions that are explicitly examined in the comparative results (Section 4) and translated into regulatory and investment implications (Section 6).

2.1 LEVELIZED COST OF HYDROGEN (LCOH)

The general formulation of the LCOH is expressed as:

$$\text{LCOH} = \frac{C_{\text{CAPEX,annual}} + C_{\text{OPEX,annual}}}{H_{\text{annual}}}$$

where:

$C_{\text{CAPEX,annual}}$ is the annualized capital expenditure (USD/year),

$C_{\text{OPEX,annual}}$ is the annual operating expenditure (USD/year),

H_{annual} is the annual hydrogen production (kg H_2/year).

This formulation ensures that both investment and operating costs are consistently allocated over the productive lifetime of each technology. The resulting LCOH values constitute the primary output metric reported in **Section 4**, while their sensitivity to financial and market parameters informs the policy trade-offs discussed in **Section 6**.

2.2 CAPITAL EXPENDITURE (CAPEX) ANNUALIZATION

Total capital expenditure includes equipment costs, installation, balance-of-plant components, civil works, grid integration, engineering, and commissioning. CAPEX is annualized using the Capital Recovery Factor (CRF):

$$C_{\text{CAPEX,annual}} = \text{CAPEX} \times \frac{r(1+r)^n}{(1+r)^n - 1}$$

where:

CAPEX is the total upfront investment (USD),

r is the real discount rate (dimensionless),

n is the economic lifetime of the plant (years).

This formulation explicitly captures financing costs and highlights the strong sensitivity of capital-intensive technologies—particularly electrolysis—to discount rates and investment conditions. The impact of alternative discount rate assumptions on LCOH outcomes is quantitatively assessed in Section 4.3, while their implications for public financing instruments, risk mitigation, and regulatory support mechanisms are addressed in Section 6.2.

2.3 OPERATING EXPENDITURE (OPEX)

Operating expenditure is expressed on an annual basis and decomposed as:

$$C_{\text{OPEX,annual}} = C_{\text{feedstock}} + C_{\text{energy}} + C_{\text{O\&M}} + C_{\text{utilities}}$$

For water electrolysis, OPEX is dominated by electricity costs:

$$C_{\text{energy}} = P_{\text{elec}} \times E_{\text{specific}} \times H_{\text{annual}}$$

where:

- P_{elec} is the electricity price (USD/kWh),
- E_{specific} is the specific electricity consumption (kWh/kg H_2).

For ethanol steam reforming, OPEX is primarily driven by ethanol feedstock costs:

$$C_{\text{feedstock}} = P_{\text{ethanol}} \times F_{\text{ethanol}} \times H_{\text{annual}}$$

where:

- P_{ethanol} is the ethanol price (USD/L or USD/GJ),
- F_{ethanol} is the ethanol consumption per kilogram of hydrogen.

These cost decompositions enable a transparent attribution of LCOH differences observed in Section 4.1 and 4.2 and support the pathway-specific policy recommendations regarding electricity market design and biofuel pricing frameworks developed in Section 6.1.

2.4 SENSITIVITY ANALYSIS

Sensitivity analysis plays a central role in methodology. Key economic and technical parameters are systematically varied, including:

- Electricity prices,
- Ethanol prices,
- CAPEX of electrolyzers and reformers,
- Discount rate,
- Capacity factor and utilization rate.

The resulting sensitivity ranges are reported in Section 4, where they define the cost envelopes and competitiveness rankings of each hydrogen pathway. These results are subsequently interpreted in Section 6 to assess the effectiveness of alternative policy instruments—such as long-term power purchase agreements, biofuel certification schemes, and financial de-risking mechanisms—in shaping hydrogen outcomes.

All assumptions are aligned with Brazilian conditions, drawing on national energy statistics, biofuel price indicators, and internationally recognized technology cost benchmarks. By explicitly linking techno-economic outcomes to regulatory and market variables, the methodological framework establishes a direct bridge between quantitative results and the policy discussion, ensuring coherence between Sections 2, 4, and 6.

3. HYDROGEN PRODUCTION PATHWAYS

3.1 WATER ELECTROLYSIS

Hydrogen production via water electrolysis relies on the conversion of electrical energy into chemical energy by splitting water molecules into hydrogen and oxygen. In the Brazilian context, the attractiveness of electrolysis is closely linked to the country's renewable electricity profile, characterized by high shares of hydropower, wind, and solar generation.

The cost structure of electrolysis is dominated by CAPEX, particularly the electrolyzer stack and associated power electronics. Operating costs are primarily driven by electricity prices, making electrolysis highly sensitive to power market design, grid tariffs, and access to long-term power purchase agreements.

While electrolysis offers scalability and strong alignment with long-term decarbonization goals, its economic performance remains contingent on sustained reductions in electrolyzer costs and access to low-cost renewable electricity.

3.2 ETHANOL STEAM REFORMING

Ethanol steam reforming is a thermo-chemical process that converts ethanol and water into hydrogen and carbon dioxide at elevated temperatures. In Brazil, this pathway benefits from a globally competitive ethanol industry with established supply chains, infrastructure, and policy support mechanisms.

Unlike electrolysis, ethanol steam reforming exhibits relatively lower CAPEX but significantly higher OPEX, dominated by the cost of ethanol feedstock. As a result, hydrogen costs from reforming are highly sensitive to ethanol prices, which are influenced by agricultural productivity, fuel blending mandates, and international commodity markets.

From a systems perspective, ethanol reforming leverages existing bioenergy assets and offers a near-term, scalable hydrogen option, particularly for industrial clusters already integrated with ethanol logistics.

4. ECONOMIC RESULTS AND COST STRUCTURES

This section presents the quantitative economic results obtained from the Levelized Cost of Hydrogen (LCOH) framework introduced in Section 2. The results explicitly show how differences in capital intensity, operating cost composition, and exposure to market variables translate into distinct cost ranges and competitiveness conditions for hydrogen production pathways in Brazil. By decomposing LCOH into CAPEX- and OPEX-related components, the analysis enables a transparent attribution of cost differentials across technologies, as anticipated in Sections 2.2 and 2.3, and provides the empirical basis for the policy discussion developed in Section 6.

Table 1 summarizes the modeled LCOH ranges across technologies and scenarios, providing a numerical reference for the detailed cost structure analysis that follows.

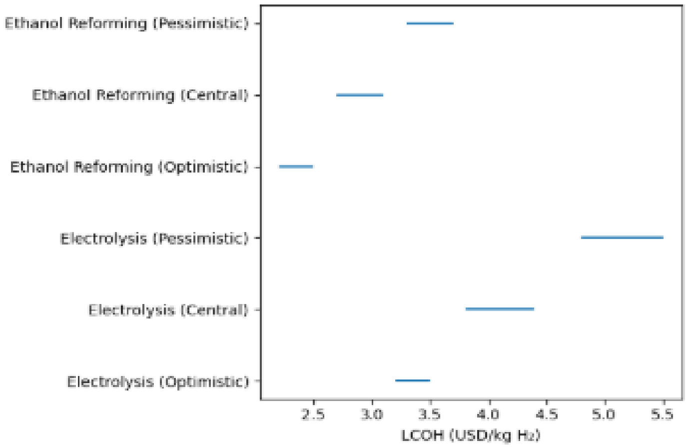
Table 1 | Summary of modeled LCOH ranges for hydrogen production pathways in Brazil

Technology	Scenario	LCOH (USD/kg H_2)	Key assumptions
Water electrolysis	Optimistic	3.2–3.5	Renewable PPA ≈ USD 0.037/kWh, high capacity factor
Water electrolysis	Central	3.8–4.4	Average electricity prices, current CAPEX
Water electrolysis	Pessimistic	4.8–5.5	Spot electricity exposure, high WACC
Ethanol steam reforming	Optimistic	2.2–2.5	Competitive ethanol prices, high utilization
Ethanol steam reforming	Central	2.7–3.1	Average ethanol prices
Ethanol steam reforming	Pessimistic	3.3–3.7	High ethanol prices, low utilization

Source: Authors' calculations based on the LCOH framework described in Section 2.

Chart 1 presents the modeled ranges of the Levelized Cost of Hydrogen (LCOH) for different hydrogen production pathways in Brazil under optimistic, central, and pessimistic scenarios. The results indicate that ethanol steam reforming yields consistently lower and less variable hydrogen production costs across scenarios, reflecting its lower capital intensity and reliance on biofuel prices. By contrast, hydrogen produced via water electrolysis displays a broader range of LCOH values, driven primarily by variations in electricity prices, capital costs, and financing conditions.

Chart 1 | Modeled LCOH ranges for hydrogen production pathways in Brazil



Source: Authors' calculations based on the LCOH framework described in Section 2.

4.1 CAPEX STRUCTURE, CAPITAL INTENSITY, AND COST IMPLICATIONS

For water electrolysis, capital expenditure represents the dominant cost component in hydrogen production. Under Brazilian conditions, modeled total CAPEX values for electrolytic hydrogen range between USD 900–1,400 per kW, depending on electrolyzer technology, scale, and balance-of-plant configuration. When annualized using discount rates between 8% and 12% and plant lifetimes of 20 years, CAPEX-related costs contribute approximately USD 1.2–2.0 per kg H_2, corresponding to 40–60% of total LCOH in most scenarios.

As a result, the total LCOH for water electrolysis spans a relatively wide range, from approximately USD 3.0/kg H_2 in optimistic scenarios—characterized by low financing costs, high capacity factors (>70%), and access to low-cost renewable electricity—to USD 5.0/kg H_2 or higher under less favorable investment and utilization conditions. This dispersion confirms the strong sensitivity of electrolysis-based hydrogen to financing parameters, as implied by the CAPEX annualization mechanism discussed in Section 2.2.

In contrast, ethanol steam reforming exhibits substantially lower capital intensity. Modeled CAPEX values for reforming units are typically in the range of USD 300–600 per kW_{h2}, leading to annualized capital costs below USD 0.5–0.7 per kg H_2, or roughly 15–25% of total LCOH. Consequently, ethanol reforming displays markedly lower sensitivity to discount rates and financing conditions, reinforcing its relative robustness in investment-constrained environments.

4.2 OPEX STRUCTURE, FEEDSTOCK DEPENDENCE, AND COST OUTCOMES

The operating cost results further differentiate the two hydrogen pathways. For water electrolysis, electricity costs dominate OPEX, accounting for 65–80% of total operating expenditure. Assuming specific electricity consumption in the range of 50–55 kWh/kg H_2 and electricity prices between USD 0.035 and 0.070 per kWh, the electricity component alone contributes approximately USD 1.8–3.8 per kg H_2. Operation and maintenance costs remain comparatively modest, typically below USD 0.3/kg H_2.

These results explain why the lower bound of electrolytic hydrogen costs is only achieved under favorable electricity market conditions, a finding that directly informs the electricity market design discussion in Section 6.1.

For ethanol steam reforming, operating expenditure is overwhelmingly driven by ethanol feedstock costs. Using ethanol prices in the range of USD 0.45–0.75 per liter (or equivalent energy content), feedstock costs contribute approximately USD 1.6–2.8 per kg H_2, representing 60–75% of total OPEX. Operation and maintenance costs, including catalyst replacement and labor, typically remain below USD 0.4/kg H_2, while utilities play a minor role.

As a result, the total LCOH for ethanol reforming falls within a narrower range, typically between USD 2.2 and 3.5 per kg H_2, depending primarily on ethanol price assumptions and plant utilization rates. This confirms that differences in LCOH between ethanol reforming scenarios can be directly attributed to feedstock price dynamics, consistent with the formulation presented in Section 2.3.

4.3 SENSITIVITY RESULTS AND COMPETITIVENESS DOMAINS

Building on the sensitivity framework outlined in Section 2.4, the results define distinct cost envelopes for each hydrogen pathway. For electrolysis, LCOH outcomes are most sensitive to electricity prices, electrolyzer CAPEX, discount rates, and capacity factors. A reduction in electricity prices of USD 0.01/kWh, for example, lowers LCOH by approximately USD 0.5/kg H_2, highlighting the leverage of electricity market regulation.

For ethanol reforming, LCOH dispersion is dominated by ethanol price volatility and utilization rates, while variations in discount rates produce comparatively limited effects. A change of USD 0.10 per liter in ethanol prices shifts LCOH by roughly USD 0.4–0.5/kg H_2, underscoring the central role of biofuel pricing frameworks.

Rather than yielding a single cost ranking, the results identify conditional competitiveness domains. Ethanol reforming emerges as the lower-cost pathway under current biofuel price conditions, while electrolysis becomes competitive in scenarios combining low-cost renewable electricity, long-term power contracts, and reduced financing costs. These quantified results constitute the direct empirical foundation for the policy conclusions articulated in Section 6.

5. COMPARATIVE LCOH ANALYSIS

This section consolidates the quantitative results presented in Section 4 into a direct cross-pathway comparison, highlighting the conditions under which each hydrogen production route becomes economically preferred in Brazil. Rather than treating competitiveness as a fixed ranking, the comparative analysis emphasizes overlapping LCOH ranges and the parameter-driven domains that separate short-term cost advantage from longer-term strategic viability.

5.1 CROSS-PATHWAY COST COMPARISON ACROSS SCENARIOS

Across all modeled scenarios, ethanol steam reforming exhibits systematically lower LCOH levels than water electrolysis under baseline Brazilian market conditions. In the optimistic case, ethanol reforming reaches USD 2.2–2.5/kg H_2, while electrolysis remains at USD 3.2–3.5/kg H_2, even when supported by low-cost renewable PPAs and high capacity factors. In central scenarios, ethanol reforming remains in the range of USD 2.7–3.1/kg H_2, compared to USD 3.8–4.4/kg H_2 for electrolysis. Under pessimistic assumptions, ethanol reforming increases to USD 3.3–3.7/kg H_2, whereas electrolysis expands to USD 4.8–5.5/kg H_2, driven by exposure to spot electricity prices and higher financing costs (Table 1; Chart 1).

These results indicate that, within the modeled parameter space, ethanol steam reforming currently occupies the lower-cost segment of Brazil's hydrogen supply curve, while electrolysis requires a narrower set of enabling conditions to approach cost parity.

5.2 OVERLAP AND "SWITCHING POINTS" IN COMPETITIVENESS

Although ethanol reforming is consistently less expensive in the modeled ranges, the comparison also reveals a potential convergence zone between pathways. The upper bound of ethanol reforming in pessimistic scenarios (USD 3.3–3.7/kg H_2) overlaps with the lower bound of electrolysis under optimistic conditions (USD 3.2–3.5/kg H_2). This overlap defines an economically relevant "switching domain," in which relative competitiveness can shift depending on policy-induced changes in electricity contracting conditions, financing costs, or ethanol price dynamics.

In practical terms, this implies that electrolysis can become cost-competitive not solely through incremental technological improvements, but primarily through institutional and regulatory arrangements that ensure sustained access to low-cost electricity and reduce investment risk. Conversely, increases in ethanol prices or reductions in reformer utilization rates may erode the cost advantage of ethanol reforming, thereby narrowing the cost gap relative to electrolysis.

5.3 INTERPRETATION THROUGH COST STRUCTURE: WHY PATHWAYS RESPOND DIFFERENTLY

The comparative ranking is directly explained by the cost structures identified in Section 4. Electrolysis is characterized by high capital intensity and electricity-driven OPEX, which produces broader LCOH dispersion across scenarios. Ethanol reforming, in contrast, has lower CAPEX sensitivity but stronger dependence on ethanol feedstock prices, resulting in a narrower and lower cost range under most assumptions. These structural differences imply that policy instruments affect each pathway through distinct channels: electricity market design and financing conditions disproportionately shape electrolysis outcomes, while biofuel pricing frameworks and feedstock stability are decisive for reforming competitiveness.

5.4 IMPLICATIONS FOR SCENARIO DESIGN

The comparative evidence supports the conclusion that Brazil's hydrogen strategy should not be framed as a zero-sum choice between technologies. Instead, the results indicate that each pathway occupies a distinct economic niche, with ethanol reforming offering near-term cost leadership and electrolysis becoming competitive under targeted conditions of low-cost renewable power and improved financing. This comparative framing provides the analytical foundation for the sensitivity-based policy scenarios developed in Section 6, where these switching domains are translated into explicit market and regulatory configurations.

6. SENSITIVITY AND POLICY SCENARIOS

The comparative results presented in Sections 4 and 5 demonstrate that the economic performance of hydrogen production pathways in Brazil is highly sensitive to a limited set of key parameters. This section builds on the sensitivity analysis framework introduced in Section 2.4 and translates the observed cost responses into explicit policy-relevant scenarios, illustrating how different regulatory and market configurations shape hydrogen competitiveness.

Rather than treating sensitivity analysis as a purely technical exercise, the scenarios discussed below link variations in electricity prices, ethanol feedstock costs, capital intensity, and financing conditions to concrete policy choices. In doing so, the section provides an intermediate analytical layer between the techno-economic results and the broader policy implications developed in the subsequent section.

6.1 ELECTRICITY PRICE AND MARKET DESIGN SCENARIOS

Electricity prices emerge as the single most influential parameter affecting the competitiveness of water electrolysis. As shown in Section 4, a reduction of USD 0.01/kWh in electricity prices lowers the LCOH of electrolytic hydrogen by approximately USD 0.5/kg H_2. This sensitivity implies that electrolysis-based hydrogen is economically viable only under electricity market configurations that ensure sustained access to low-cost renewable power.

Policy scenarios that support such outcomes include long-term power purchase agreements (PPAs), dedicated renewable generation for hydrogen production, and tariff structures that reduce grid charges for electrolysis operating at high capacity factors. Under these conditions, electrolytic hydrogen approaches the lower bound of its modeled cost range (USD 3.2–3.5/kg H_2), as reported in Section 4. Conversely, exposure to spot market prices and conventional grid tariffs shifts electrolysis toward the upper end of its cost envelope, rendering it uncompetitive relative to ethanol reforming.

6.2 BIOFUEL PRICING AND AGRICULTURAL POLICY SCENARIOS

For ethanol steam reforming, sensitivity analysis identifies ethanol feedstock prices as the dominant cost driver. As discussed in Sections 4.2 and 4.3, variations of USD 0.10 per liter in ethanol prices translate into LCOH shifts of approximately USD 0.4–0.5/kg H_2. This strong dependence highlights the central role of agricultural productivity, fuel blending mandates, and biofuel market regulation in shaping hydrogen economics.

Policy scenarios that stabilize or moderate ethanol prices—such as predictable blending mandates, biofuel certification schemes, and productivity-enhancing agricultural policies—support hydrogen production costs in the range of USD 2.2–3.1/kg H_2. In contrast, scenarios characterized by ethanol price volatility or supply constraints push reforming costs toward the upper bound of the modeled range (USD 3.3–3.7/kg H_2), narrowing the cost advantage relative to electrolysis.

6.3 FINANCING CONDITIONS AND INVESTMENT RISK SCENARIOS

Financing conditions, captured through variations in the discount rate, affect both hydrogen pathways but with markedly different intensities. As shown in Section 4.1, the high capital intensity of electrolysis makes its LCOH particularly sensitive to discount rates and perceived investment risk. Policy scenarios that reduce financing costs—through public guarantees, concessional finance, or risk-sharing mechanisms—have a disproportionate impact on improving the competitiveness of electrolysis-based hydrogen.

By contrast, ethanol steam reforming, with its lower upfront capital requirements, exhibits comparatively limited sensitivity to discount rate assumptions. This asymmetry suggests that financial de-risking instruments are more effective when targeted at capital-intensive hydrogen pathways, while bioenergy-based routes benefit more directly from feedstock price stabilization policies.

6.4 INTEGRATED POLICY SCENARIOS AND CONDITIONAL COMPETITIVENESS

When considered jointly, the sensitivity results define a set of conditional competitiveness domains, rather than a single optimal hydrogen pathway. Ethanol steam reforming remains cost-competitive across a wide range of policy and market conditions, particularly in scenarios characterized by stable biofuel prices and moderate financing costs. Water electrolysis, in contrast, becomes competitive only under integrated policy scenarios that combine low-cost renewable electricity, favorable financing conditions, and high utilization rates.

These integrated scenarios highlight that hydrogen policy design in Brazil is not a matter of choosing between competing technologies, but of aligning regulatory instruments with the specific cost structures of each pathway. The sensitivity-based scenarios developed in this section thus provide a structured bridge between the comparative economic analysis and the strategic policy recommendations articulated in the following section.

7. POLICY IMPLICATIONS AND STRATEGIC INSIGHTS FOR BRAZIL

The economic results presented in Section 4 provide a transparent and quantitatively grounded view of the cost structures underlying alternative hydrogen production pathways in Brazil. By explicitly linking LCOH outcomes to capital intensity, operating cost composition, and exposure to market variables, the analysis moves beyond abstract comparisons and identifies concrete policy leverage points through which hydrogen competitiveness can be shaped.

The results demonstrate that the relative performance of water electrolysis and ethanol steam reforming is not determined by technological efficiency alone, but by the interaction between cost structures and regulatory environments. As shown in Section 4.1, the capital-intensive nature of electrolysis makes hydrogen costs highly sensitive to financing conditions, discount rates, and utilization levels, whereas Section 4.2 reveals that ethanol-based hydrogen is structurally driven by biofuel prices and agricultural policy dynamics. These differentiated cost drivers define distinct policy leverage points, which are explored in this section.

From a policy and extension-oriented perspective, the findings highlight that hydrogen strategies cannot be reduced to a single technological trajectory. Instead, they require pathway-specific policy instruments aligned with Brazil's institutional strengths—namely, its renewable electricity potential and its consolidated bioenergy sector. In this sense, the competitiveness domains identified in Section 4.3 provide a practical framework for public decision-makers, regulators, and regional development agencies to design targeted interventions capable of fostering hydrogen deployment while minimizing economic risk.

Accordingly, this section translates the techno-economic evidence into actionable policy insights, with particular attention to electricity market design, biofuel pricing frameworks, and financing mechanisms. By doing so, it closes the analytical loop between methodology (Section 2), results (Section 4), and policy discussion, reinforcing the contribution of this study to applied energy planning and sustainable development strategies in Brazil.

8. POLICY IMPLICATIONS

The findings suggest that Brazil is uniquely positioned to adopt a dual-track hydrogen strategy. In the short to medium term, ethanol steam reforming offers a cost-effective and scalable hydrogen source that capitalizes on existing bioenergy infrastructure. In the longer term, water electrolysis becomes increasingly attractive as renewable electricity costs decline and electrolyzer technologies mature.

Policy design plays a decisive role in shaping hydrogen outcomes. Instruments such as power purchase agreements, biofuel credit mechanisms, and carbon pricing directly influence the relative competitiveness of hydrogen pathways. Well-coordinated policies can reduce investment risk, accelerate cost reductions, and enable a smooth transition toward a diversified hydrogen economy.

CONCLUSIONS

This study provides a comprehensive comparative techno-economic and policy-oriented assessment of hydrogen production pathways in Brazil, focusing on water electrolysis powered by renewable electricity and ethanol steam reforming. By explicitly integrating engineering economics with sensitivity analysis, the article demonstrates that hydrogen economics are not technology-neutral outcomes, but rather the result of a structured interaction between cost composition, market conditions, and regulatory frameworks.

The quantitative results show that, under baseline Brazilian market conditions, ethanol steam reforming consistently delivers lower Levelized Cost of Hydrogen (LCOH) values than water electrolysis, particularly in the short to medium term. This outcome is primarily driven by the lower capital intensity of reforming technologies and the country's competitive ethanol supply chain. In contrast, electrolysis-based hydrogen exhibits broader cost dispersion and higher sensitivity to electricity prices, financing conditions, and utilization rates, becoming cost-competitive only under integrated scenarios combining low-cost renewable electricity, long-term contracting arrangements, and reduced investment risk.

Beyond the numerical comparison, the analysis highlights that each hydrogen pathway responds to distinct policy levers. Electricity market design, grid tariffs, and power purchase agreements emerge as decisive for electrolysis competitiveness, while biofuel pricing frameworks, agricultural productivity, and feedstock stability play a central role in shaping the economics of ethanol reforming. These differentiated sensitivities imply that hydrogen policy cannot rely on uniform instruments, but must be tailored to the structural characteristics of each production route.

From a strategic perspective, the findings support the adoption of a dual-track hydrogen strategy in Brazil. Ethanol steam reforming can act as a near-term, scalable solution that leverages existing bioenergy assets and industrial infrastructure, while water electrolysis represents a long-term pathway aligned with deep decarbonization objectives as renewable electricity costs decline and electrolyzer technologies mature. Rather than competing, these pathways are shown to be complementary within a diversified hydrogen economy.

Methodologically, the study contributes by moving beyond static cost rankings and explicitly mapping conditional competitiveness domains through sensitivity analysis. This approach provides decision-makers with a more realistic representation of uncertainty and policy leverage points, enhancing the relevance of techno-economic assessments for applied energy planning and regulatory design.

Finally, the Brazilian case illustrates how countries with heterogeneous energy endowments can design hydrogen strategies that balance short-term economic efficiency with long-term technological transformation. Future research may extend this framework by incorporating dynamic learning effects, carbon pricing mechanisms, and life-cycle emissions, further strengthening the analytical bridge between hydrogen economics, climate policy, and sustainable development.

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