Techno-economic assessment of the use of green hydrogen: case study in the ceramic industry

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H2

Resumen

La industria cerámica en Brasil consume volúmenes significativos de gas natural, generalmente para atender procesos que requieren altas temperaturas. Así, el uso de H2 de bajo carbono se convierte en una alternativa potencial para ser introducida en la matriz energética del sector, bajo una modalidad de auto-generación y auto-consumo, con el fin de reemplazar parcialmente el consumo de gas natural en procesos industriales. Se realiza un modelado técnico-económico, utilizando la herramienta H2V-IEPUC, sobre un estudio de caso realizado en colaboración con una empresa de la industria cerámica. La escala de producción y uso de H2 se estimó con base en proyectos internacionales y tomando como referencia los procesos industriales actualmente implementados en una fábrica. La viabilidad del proyecto de hidrógeno verde se demuestra mediante un análisis de sensibilidad con variables técnicas y económicas, además de presentar un escenario determinista de viabilidad. La comprensión del estudio de caso contribuye a los subsectores de la industria al arrojar luz sobre las ventajas y barreras relacionadas con la incorporación de H2 de bajo carbono en las operaciones, contribuyendo a la construcción de proyectos ambiental y económicamente sostenibles.

PALABRAS CLAVE: Palabras clave: hidrógeno, electrólisis, oxígeno, proceso de alta temperatura, cerámica.

Abstract

The ceramic industry in Brazil consumes significant volumes of natural gas, usually for attending to processes that require high temperatures. Thus, the use of low-carbon H2 becomes a potential alternative to be introduced into the sector's energy matrix, under a self-generation and self-consumption modality, in order to partially replace natural gas in industrial processes. Technical-economic modeling is carried out, using the H2V-IEPUC tool, on a case study conducted in partnership with a ceramic industry company. The scale of production and use of H2 were estimated based on international projects and taking as a reference industrial processes currently implemented at a factory. The feasibility of the green hydrogen project is demonstrated by carrying out a sensitivity analysis with technical and economic variables, in addition to presenting a deterministic feasibility scenario. The understanding of the case study contributes to industry subsectors by shedding light on the advantages and barriers related to the incorporation of low-carbon H2 in operations, contributing to the construction of projects that are environmentally and economically sustainable.

KEYWORDS: hydrogen, electrolysis, oxygen, high-temperature process, ceramic

1. INTRODUCTION

The ceramic industry can be divided into two main categories: red ceramics and white ceramics. Red ceramics are typically associated with large-scale structural uses in civil construction (bricks, tiles, etc.), and are produced by using firewood as the predominating energy source in Brazil (EPE, 2018). White ceramics, on the other hand, generally consist of higher-quality products (flooring, tiles, porcelain, etc.) that serve more specific functions and require a higher energy intensity in manufacturing (e.g., in the drying process). In this case, natural gas predominates in Brazil as the main fuel along such a manufacturing chain. Among the emerging uses of H_2, processes involving high-temperature heat (above 400 ºC) can benefit from this resource as a form of decarbonization, presenting as a competitive alternative to electrification (IEA, 2024; ENGIE, 2022). In this way, the energetic use of hydrogen can help preserve existing industrial assets and avoid the need for developing disruptive technologies.

Green H_2, derived from water electrolysis using renewable energy (such as hydric, solar, and wind), is an energy source capable of serving this class of processes as a substitute for fossil fuels. In particular, the Brazilian electricity grid could be suitable for green hydrogen production, since hydropower stands out with a share of almost 60% as one of the main primary energy sources (EPE, 2024). As long as the hydric scenario in the country is favorable, the grid can sustain a low-carbon intensity with reliable provision, for example, facilitating the certification of hydrogen in strict schemes (CCEE, 2024). Overall, the combination of renewable electricity resources in Brazil can allow elevated operational factors, enabling the economic feasibility of electrolysis projects while guaranteeing the environmental attribute of hydrogen.

Notably, international experiences in the ceramics industry have adopted pilot plants to use green hydrogen. For example, a ceramic company in Villareal, Spain, has invested in the GREENH2KER decarbonization project, which aims to replace 50% of natural gas with green H_2 (IBERDROLA, 2021). Another recent experience that endorses the technical feasibility of using a hydrogen-natural gas mixture in the ceramic industry is a project developed in Castellarano, Italy. Success was reported for tests with fuel blends containing 7% H2 to decarbonize the operation of a kiln, and there is an expectation to use mixtures with up to 50% H2 (IRIS, 2024).

Finally, although carbon credits tend to be the main coproduct in economic assessments involving low-carbon H2, the O2 coproduced in electrolysis is usually neglected. Actually, only specific industrial sectors (steel industry, healthcare systems in hospitals, submarine projects) use it at relevant scales (IEA, 2023). Dedicated O_2 production systems tend to be costly for use in enhanced combustion processes, and therefore combustion is conducted commonly with air as comburent. It is noteworthy that some studies are giving purpose to this byproduct. Novaes et al. (2024) evaluated a Power-to-Liquid process sourced with green H2 to produce wax and syncrude as main products. The revenue associated with O2 presented a share of 13% among the outputs, being also almost four times more representative than the selling of carbon credits. Assunção et al. (2025) modeled the use of an electrolysis system in order to supply H2 for fuel cell vehicles (i.e., ambulances) while O2 was stored for attending to the healthcare systems in a hospital. Avoiding the cost of buying O2 allowed a reduction of the levelized cost of Hydrogen (LCOH) from 4.96 to 2.60 USD/kg. Finally, León et al. (2024) studied a bolder model for a cement factory in Spain, in which synfuels are produced by combining CO2 from flue gases and hydrogen from electrolysis; the coproduced O2 was appraised through an oxy-combustion applied to a calcination process. Thus, the possibility of designating a concrete use for O2 can promote the economic feasibility of H2 derived from water electrolysis.

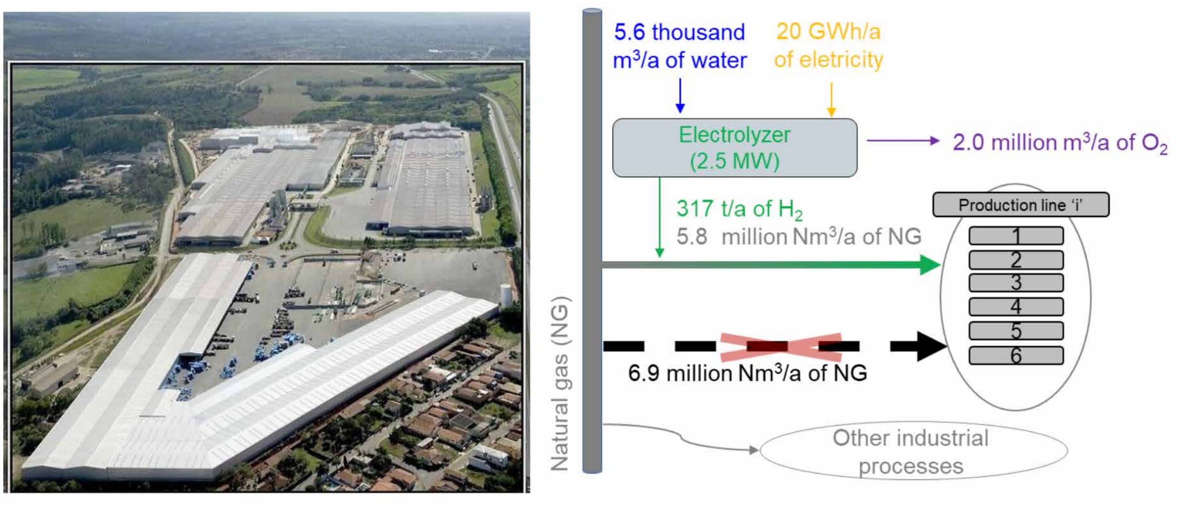
In this context, this study aims to assess the partial substitution of natural gas with green H_2 in the white ceramic sector, focusing on a drying process at a concrete ceramic facility in São Paulo state, Brazil (DELTA, 2024). A feasible substitution level and electrolyzer capacity scale are assumed in the simulation, as exemplified by the presented international projects within the ceramic industry. Variables surrounding this substitution are evaluated with the H2V-IEPUC model (CNI, 2024). The tool enables a sensitivity analysis useful to track deterministic scenarios that are attractive to industry companies, according to technical, economic, and environmental metrics. Therefore, this study aims to track conditioning factors that enable the introduction of low-carbon hydrogen in the ceramic industry, within the framework of a Brazilian company, representing a novelty for the literature.

Within the scope of assessing the feasibility of using hydrogen as a fuel for ceramic processes, the objectives of this paper are to model the incremental cash flow and the net present value (NPV) of the substitution project, within the Brazilian company technic-economic framework; to quantify the main partakes in the cost of green hydrogen in the levelized cost metric (LCOH) as well as revenues associated to coproducts (CO2 credits and O2); and consider a sensitivity analysis on NPV with the CAPEX and electricity cost, identified as key parameters to be combined for the sake of the project's feasibility. The modeling and planning of partial substitution of natural gas in a dedicated branch of the factory allow the industrial player to kick off an initial pilot phase, enabling the introduction of green H_2 in the energy matrix. This means the adoption of a project with a low technical risk, such as intermediate product drying. Depending on the internal experience gained and the technical-operational success in the H_2 usage, the player could expand the system rationally, either by safely increasing the natural gas substitution in existing processes or by extending the H_2 use to other processes within the factory.

2. METHODS

The ceramic-industry player facilities are located in Rio Claro, in São Paulo's interior, Brazil (Figure 1), contributing to the municipality's status as the largest ceramics production center in the Americas and representing a significant production scale globally. This allowed the study case to consider meaningful production scale magnitudes within the ceramics sector. In the factory, there are around 10 production lines established to process raw materials into ceramic products by using natural in kilns and dryers.

Figure 1 – Ceramic factory in São Paulo State, Brazil (left) and evaluated study case (right)



Source: elaborated by the authors with data from Delta (2024).

The factory has a dedicated natural gas line supplying six dryers, each consuming an average of 3,450 Nm^3/d of natural gas. An electrolysis system was sized to replace 15% of the fossil fuel. Given an annual factory operation of 8,000 hours (91.3% operational factor), the current annual consumption of 6.9 million m^3 of natural gas could be reduced to 5.8 million m^3/yr with the use of H_2 (317 tons of H_2 per year) generated by a 2.5 MW electrolyzer (ENZE CUMMINS, 2023). The simulation of physical and cash flows and the economic analysis for the fuel replacement project were conducted using the H2V-IEPUC tool (CNI, 2024).

The input variables are as follows. The technical variables of the electrolyzer were: specific electricity consumption of 61.7 kWh/kg H_2, specific water consumption of 16.92 l/kg, coproduction of 8 kg of O_2/kg H_2, and an annual electrolyzer stack degradation rate of 1% (Khan et al., 2021). The main economic variables are listed in Table 1.

Table 1 – Key input variables for the economical-financial modeling

CAPEXelectrolyzer	7,263 BRL/kW	Other investments	50% of CAPEXelectrolyzer
O&M	5% a.a.	Membrane replacement	20% of CAPEXelectrolyzer
Residual value	30% do CAPEXelectrolyzer	Time horizon	20 years
CAPEX allocation	2 years, with 80% in the 1st year	Electricity cost	300 BRL/MWh
Natural gas cost	4.30 BRL/Nm3	Water cost	0.6 BRL/m3
Carbon credits	250 BRL/t CO2		

Sources: elaborated by the authors with data from Khan et al. (2021) and Delta (2024).

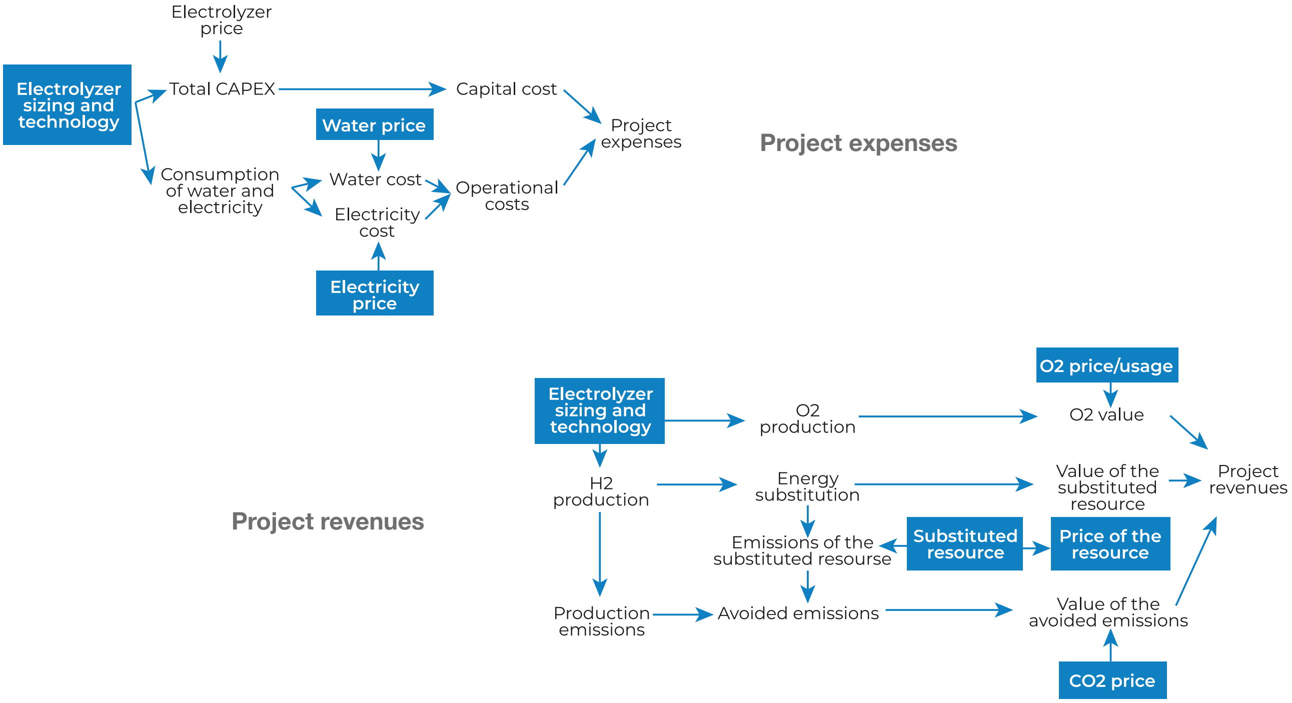
The electrolyzer CAPEX (1,452 USD/kW) and annual OPEX (5% of electrolyzer CAPEX) were adapted from Khan et al. (2021). Besides the electrolyzer CAPEX, 50% of CAPEX was added due to importation, EPC (engineering, procurement, and construction) activities, and contingencies. The electrolyzer project was simulated over 20 years. The total investment (27 million BRL) was allocated in the first two years, with 80% in the first year. Besides the annual OPEX, the need for membrane replacement in the electrolyzer (20% of electrolyzer CAPEX) was considered after 75,000 hours of operation. The cost of water for the electrolysis was assumed to be 0.6 BRL/m^3. The annual water demand of 5,600 m^3 can be sourced from the company's water resources, representing a small volume and low environmental impact within the factory operations (Delta, 2024). The electricity cost of 300 BRL/MWh was considered appropriate to the factory's circumstances. Figure 2 pictures the modeling scheme implemented to build the cash flow.

For the incremental cash flow assessment, the replaced natural gas was considered an avoided cost (revenue), valued at 4.30 BRL/Nm^3. According to the reduction of natural gas consumption (emission factor of 56.15 gCO_2eq/MJ) (IPCC, 2014), revenues from carbon credits were valued at 250 BRL/t CO_2eq.

Given the proximity of hydrogen production to its final use, the O_2 produced from electrolysis was considered for oxygen-enhanced combustion (OEC) purposes (CSN, 2020; Wu et al., 2010). Therefore, through a thermodynamic analysis focused on adiabatic flame temperature (Law, 2010), aiming at enriching the combustion air with O_2 concentrations lower than 30% v/v, a technical potential of saving 0.47 m^3 of natural gas/m^3 of O_2 produced by electrolysis was adopted (Castiñeiras-Filho, et al., 2024). In this way, the appraisal of O_2 aggregates revenues through natural gas savings and the generation of carbon credits.

After entering the input variables, the H2V-IEPUC tool (CNI, 2024) reports many relevant outputs inherent to the simulated incremental cash flow. The main output variables are the net present value (NPV), the internal rate of return (IRR), the levelized cost of hydrogen (LCOH) and its break-down into components, and the competitiveness price of natural gas that equalizes the implementation of the hydrogen project with the business as usual case. Figure 2 pictures a scheme representing how the tools gather the input variables and build up the cash flows. For more details about the modeling of the cash flow, a manual is provided with the tool (CNI, 2024).

Figure 2 – Simplified scheme for estimating revenues and expenses in the modeling



Source: elaborated by the authors.

According to the methodology outlined above, a technical and economic analysis was conducted for two scenarios: a base (conservative) scenario that ignores the potential value of O_2; and a promising scenario that considers O_2 appreciation. It is important to highlight that the latter scenario disregards costs related to O_2 processing and conditioning from electrolysis, as well as other costs associated with equipment and infrastructure adaptations needed for OEC implementation. In addition to the deterministic results for the context presented in this methodology, a sensitivity analysis of the NPV was performed concerning the most impactful variables: natural gas cost, electricity cost, and electrolyzer CAPEX.

3. RESULTS AND DISCUSSION

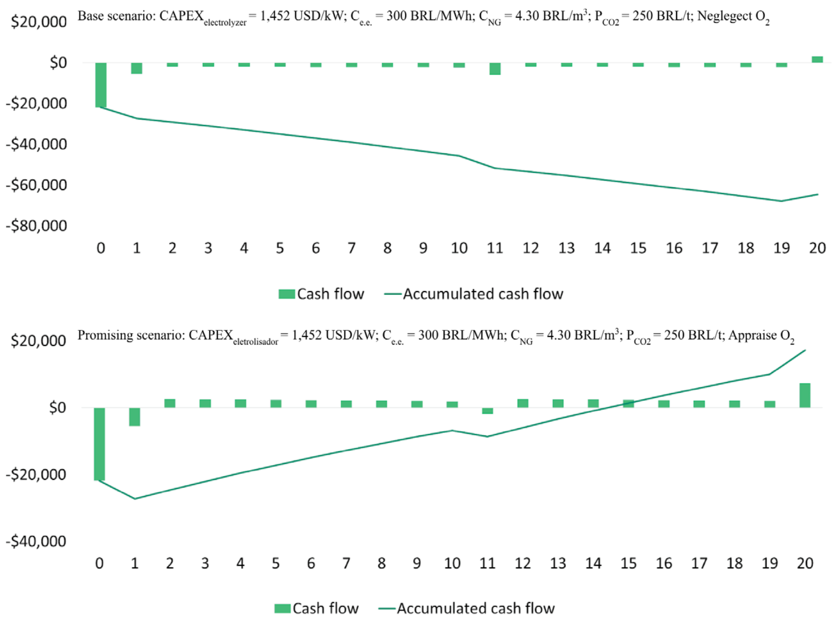
3.1. Analysis of Incremental Cash Flow for the Base and Promising Scenarios

The cash flow and accumulated cash flow of the base and promising scenarios are presented in Figure 3. The base scenario demonstrates the economic unfeasibility of the project, based on the economic assumptions outlined in Table 1. A major issue was that the annual costs (O&M, electricity, etc.) consistently exceeded the revenues (natural gas avoided cost and carbon credits) associated with the partial substitution of natural gas by green H_2. Notably, in year 11, the need to replace the electrolyzer membrane after 75,000 hours of operation showed up as a relevant cost, further impacting the economic viability of the project. Therefore, the base scenario is unfeasible, as it resulted in a negative NPV of -50 million BRL and a strictly decreasing cash flow.

On the other hand, the promising scenario demonstrated that the ability to valorize the O_2 produced from electrolysis enables the project's accumulated cash flow to grow, reflecting the generation of revenues greater than the operational costs. It is noteworthy that the use of O_2 to displace 0.47 m^3 of gas/m^3 of O_2, with a natural gas cost of 4.30 BRL/m^3, generates a value of approximately 2.021 BRL/m^3 of O_2. In addition to this revenue from fuel savings, an additional CO_2 emission reduction of 0.972 $kgCO_2/m^3$ O_2 valued at 250 BRL/t CO_2 results in an extra revenue of 0.243 BRL/m^3 of O_2. This potential valuation highlights the importance of conducting R&D to explore the utilization of O_2 in industrial processes or even to seek its commercialization with third parties.

Finally, although Figure 3 shows that the scenario appraising O_2 seems to have a favorable cash flow, its NPV was equal to -0.822 million BRL and the IRR was 4.7. From an objective perspective, even the valorization of O_2 is not sufficient to approve the implementation of the electrolysis project; however, the feasibility was very close with regard to the discount rate of 5%. This result demonstrates that access to low-interest financing options, crucial for stimulating decarbonization projects, could contribute to the adoption of H_2 in the ceramics sector.

Figure 3 – Cash flow overview for the base scenario (above) and the promising scenario (below)

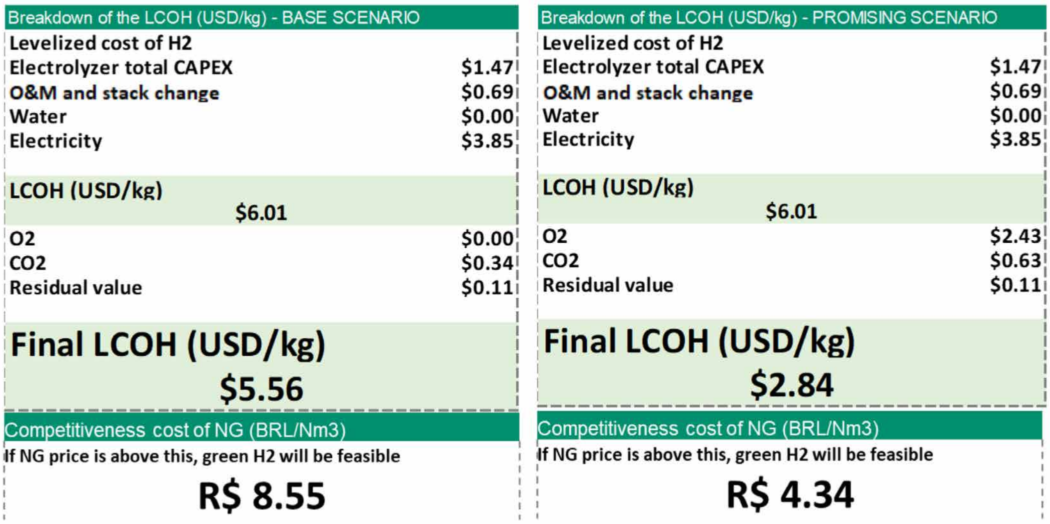


Source: elaborated by the authors.

3.2. Levelized Cost of Hydrogen (LCOH) structure in the scenarios

Figure 4 demonstrates the breakdown of the Levelized Cost of Hydrogen (LCOH) in the evaluated scenarios, as well as the cost of the fossil fuel above which the use of hydrogen becomes competitive. The base scenario resulted in an LCOH of 5.56 USD/kg of H2. The main components were the cost of electricity (3.85 USD/kg, 64% of costs) and the CAPEX of the electrolyzer (1.47 USD/kg, 24.5% of costs). Therefore, reducing these costs is relevant to make the electrolysis projects viable and minimize the cost of the hydrogen produced. Among the cost reducers, the carbon credits contribute to a reduction of 0.34 USD/kg of H2 produced. Additionally, for the sake of the economic competitiveness of H2, natural gas would need to cost 8.55 BRL/m3 in the base scenario, nearly double the cost adopted (4.30 BRL/m3), demonstrating the unfeasibility of the project.

Figure 4 – LCOH for the base scenario (on the left) and promising scenario (right), and competitiveness cost of the fossil source.



Breakdown of the LCOH (USD/kg) - BASE SCENARIO	
Levelized cost of H2	
Electrolyzer total CAPEX	**$1.47**
O&M and stack change	**$0.69**
Water	**$0.00**
Electricity	**$3.85**
LCOH (USD/kg)	
$6.01	
O2	**$0.00**
CO2	**$0.34**
Residual value	**$0.11**
Final LCOH (USD/kg)	
$5.56	
Competitiveness cost of NG (BRL/Nm3)	
If NG price is above this, green H2 will be feasible	
R$ 8.55	

Breakdown of the LCOH (USD/kg) - PROMISING SCENARIO	
Levelized cost of H2	
Electrolyzer total CAPEX	**$1.47**
O&M and stack change	**$0.69**
Water	**$0.00**
Electricity	**$3.85**
LCOH (USD/kg)	
$6.01	
O2	**$2.43**
CO2	**$0.63**
Residual value	**$0.11**
Final LCOH (USD/kg)	
$2.84	
Competitiveness cost of NG (BRL/Nm3)	
If NG price is above this, green H2 will be feasible	
R$ 4.34	

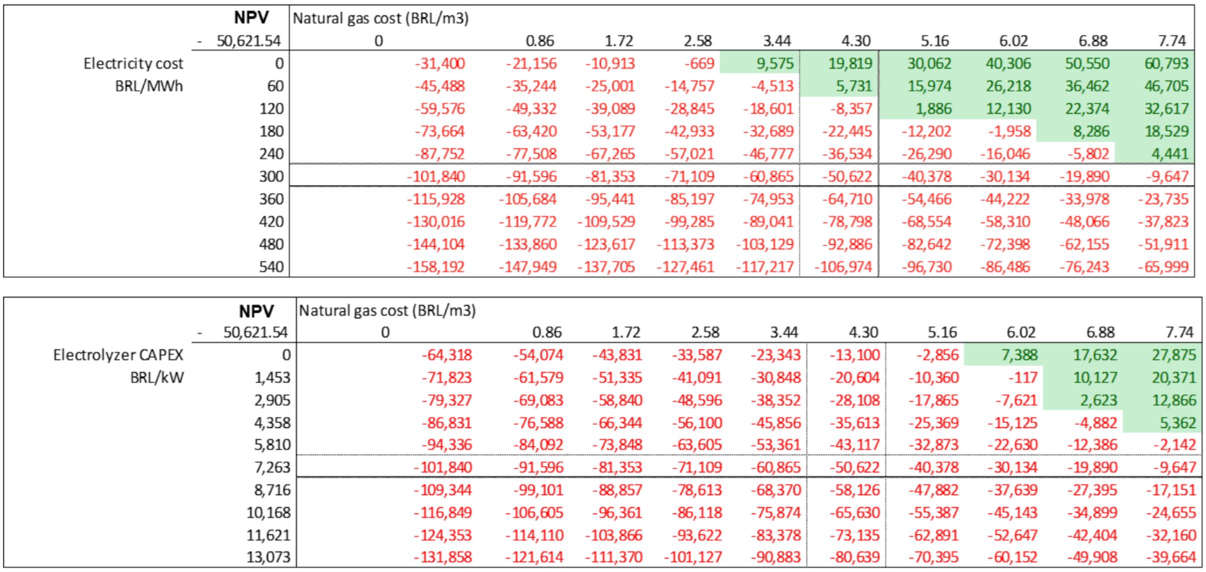
Source: elaborated by the authors with the tool in CNI (2024)

In the promising case, the O2 contributed to a reduction of 2.43 USD/kg in the LCOH, in addition to increasing the carbon credit revenue to a total of 0.63 USD/kg of H2. Thus, the LCOH in the promising case reached 2.84 USD/kg, proposing a competitiveness value for the fossil fuel of 4.34 BRL/m3. As assessed in the previous section, where the natural gas price was established at 4.30 BRL/m3, the substitution project is very close to being viable. Therefore, a structural increase in the price of natural gas over the project's time horizon, for example, can turn the NPV positive, assuming that the other assumptions in Table 1 remain constant.

3.3. Analysis of the sensitivity of the NPV to relevant economic variables

As observed in the LCOH components, the relevant costs are: the cost of the fossil fuel, the electricity cost, and the electrolyzer CAPEX. Figures 5 and 6 show the NPV sensitivity to variations in these parameters for the base and promising scenarios, respectively.

Figure 5 – Sensitivity analysis of NPV in the base scenario (neglecting O2)



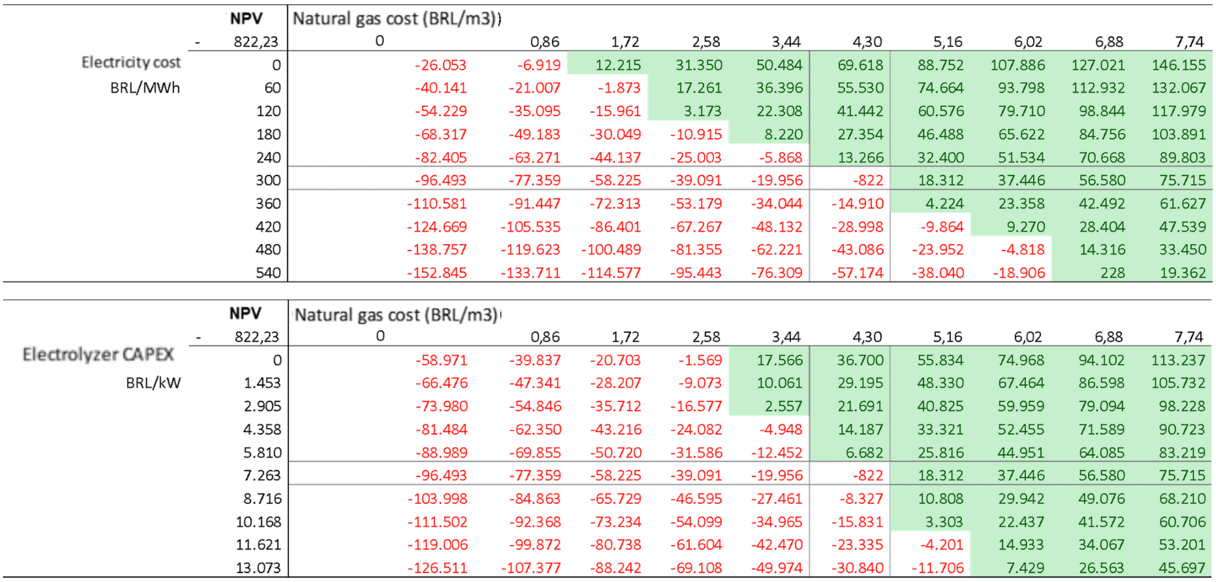
	NPV	Natural gas cost (BRL/m3)									
	- 50,621.54	0	0.86	1.72	2.58	3.44	4.30	5.16	6.02	6.88	7.74
Electricity cost	0	-31,400	-21,156	-10,913	-669	9,575	19,819	30,062	40,306	50,550	60,793
BRL/MWh	60	-45,488	-35,244	-25,001	-14,757	-4,513	5,731	15,974	26,218	36,462	46,705
	120	-59,576	-49,332	-39,089	-28,845	-18,601	-8,357	1,886	12,130	22,374	32,617
	180	-73,664	-63,420	-53,177	-42,933	-32,689	-22,445	-12,202	-1,958	8,286	18,529
	240	-87,752	-77,508	-67,265	-57,021	-46,777	-36,534	-26,290	-16,046	-5,802	4,441
	300	-101,840	-91,596	-81,353	-71,109	-60,865	-50,622	-40,378	-30,134	-19,890	-9,647
	360	-115,928	-105,684	-95,441	-85,197	-74,953	-64,710	-54,466	-44,222	-33,978	-23,735
	420	-130,016	-119,772	-109,529	-99,285	-89,041	-78,798	-68,554	-58,310	-48,066	-37,823
	480	-144,104	-133,860	-123,617	-113,373	-103,129	-92,886	-82,642	-72,398	-62,155	-51,911
	540	-158,192	-147,949	-137,705	-127,461	-117,217	-106,974	-96,730	-86,486	-76,243	-65,999

	NPV	Natural gas cost (BRL/m3)									
	- 50,621.54	0	0.86	1.72	2.58	3.44	4.30	5.16	6.02	6.88	7.74
Electrolyzer CAPEX	0	-64,318	-54,074	-43,831	-33,587	-23,343	-13,100	-2,856	7,388	17,632	27,875
BRL/kW	1,453	-71,823	-61,579	-51,335	-41,091	-30,848	-20,604	-10,360	-117	10,127	20,371
	2,905	-79,327	-69,083	-58,840	-48,596	-38,352	-28,108	-17,865	-7,621	2,623	12,866
	4,358	-86,831	-76,588	-66,344	-56,100	-45,856	-35,613	-25,369	-15,125	-4,882	5,362
	5,810	-94,336	-84,092	-73,848	-63,605	-53,361	-43,117	-32,873	-22,630	-12,386	-2,142
	7,263	-101,840	-91,596	-81,353	-71,109	-60,865	-50,622	-40,378	-30,134	-19,890	-9,647
	8,716	-109,344	-99,101	-88,857	-78,613	-68,370	-58,126	-47,882	-37,639	-27,395	-17,151
	10,168	-116,849	-106,605	-96,361	-86,118	-75,874	-65,630	-55,387	-45,143	-34,899	-24,655
	11,621	-124,353	-114,110	-103,866	-93,622	-83,378	-73,135	-62,891	-52,647	-42,404	-32,160
	13,073	-131,858	-121,614	-111,370	-101,127	-90,883	-80,639	-70,395	-60,152	-49,908	-39,664

Note: Other parameters are constant as in Table 1. Values in green highlight scenarios where the NPV is greater than zero.

Source: elaborated by the authors with the tool in CNI (2024)

Figure 6 – Sensitivity analysis of NPV in the promising scenario (appraising O2)



	NPV	Natural gas cost (BRL/m3))									
	- 822,23	0	0,86	1,72	2,58	3,44	4,30	5,16	6,02	6,88	7,74
Electricity cost	0	-26.053	-6.919	12.215	31.350	50.484	69.618	88.752	107.886	127.021	146.155
BRL/MWh	60	-40.141	-21.007	-1.873	17.261	36.396	55.530	74.664	93.798	112.932	132.067
	120	-54.229	-35.095	-15.961	3.173	22.308	41.442	60.576	79.710	98.844	117.979
	180	-68.317	-49.183	-30.049	-10.915	8.220	27.354	46.488	65.622	84.756	103.891
	240	-82.405	-63.271	-44.137	-25.003	-5.868	13.266	32.400	51.534	70.668	89.803
	300	-96.493	-77.359	-58.225	-39.091	-19.956	-822	18.312	37.446	56.580	75.715
	360	-110.581	-91.447	-72.313	-53.179	-34.044	-14.910	4.224	23.358	42.492	61.627
	420	-124.669	-105.535	-86.401	-67.267	-48.132	-28.998	-9.864	9.270	28.404	47.539
	480	-138.757	-119.623	-100.489	-81.355	-62.221	-43.086	-23.952	-4.818	14.316	33.450
	540	-152.845	-133.711	-114.577	-95.443	-76.309	-57.174	-38.040	-18.906	228	19.362

	NPV	Natural gas cost (BRL/m3)									
	- 822,23	0	0,86	1,72	2,58	3,44	4,30	5,16	6,02	6,88	7,74
Electrolyzer CAPEX	0	-58.971	-39.837	-20.703	-1.569	17.566	36.700	55.834	74.968	94.102	113.237
BRL/kW	1.453	-66.476	-47.341	-28.207	-9.073	10.061	29.195	48.330	67.464	86.598	105.732
	2.905	-73.980	-54.846	-35.712	-16.577	2.557	21.691	40.825	59.959	79.094	98.228
	4.358	-81.484	-62.350	-43.216	-24.082	-4.948	14.187	33.321	52.455	71.589	90.723
	5.810	-88.989	-69.855	-50.720	-31.586	-12.452	6.682	25.816	44.951	64.085	83.219
	7.263	-96.493	-77.359	-58.225	-39.091	-19.956	-822	18.312	37.446	56.580	75.715
	8.716	-103.998	-84.863	-65.729	-46.595	-27.461	-8.327	10.808	29.942	49.076	68.210
	10.168	-111.502	-92.368	-73.234	-54.099	-34.965	-15.831	3.303	22.437	41.572	60.706
	11.621	-119.006	-99.872	-80.738	-61.604	-42.470	-23.335	-4.201	14.933	34.067	53.201
	13.073	-126.511	-107.377	-88.242	-69.108	-49.974	-30.840	-11.706	7.429	26.563	45.697

Note: Other parameters are constant as in Table 1. Values in green highlight scenarios where the NPV is greater than zero.

Source: elaborated by the authors with the tool in CNI (2024)

The base scenario shows that only with an electricity cost between 60 and 120 BRL/MWh would be possible to make the project viable, given the reference price for natural gas of 4.30 BRL/m³. If the cost of natural gas increases by 50%, an electricity cost as low as 120 BRL/MWh would be necessary to achieve economic feasibility, for example. Regarding the electrolyzer CAPEX, a 40% cost reduction (i.e., 4,358 BRL/kW) would only make the project viable for natural gas prices as high as 7.74 BRL/m³.

In the promising scenario, the contexts that make the decarbonization project viable are more diverse. An electricity cost of around 180 BRL/MWh would already make the project viable even if the cost of natural gas was reduced by 20%, to competitive levels as low as 3.44 BRL/m³. Regarding the electrolyzer CAPEX, a 40% reduction of it would also favor the viability of the project.

Thus, the sensitivity analyses highlight that the accessibility of the ceramics industry to low electricity costs is essential for the rational introduction of green H2 into its energy matrix. In the Brazilian context, the industry can invest in distributed or self-generation projects with renewable energy, which may allow access to more competitive electricity costs. This alternative benefits either the electrolysis project or other industrial operations, besides ensuring a renewable energy backing for the H2 produced and the electricity matrix of the factory. In addition to this route, the factory can seek negotiations in the free energy market so as to achieve electricity costs in accordance with the scope of producing H2 for decarbonization purposes.

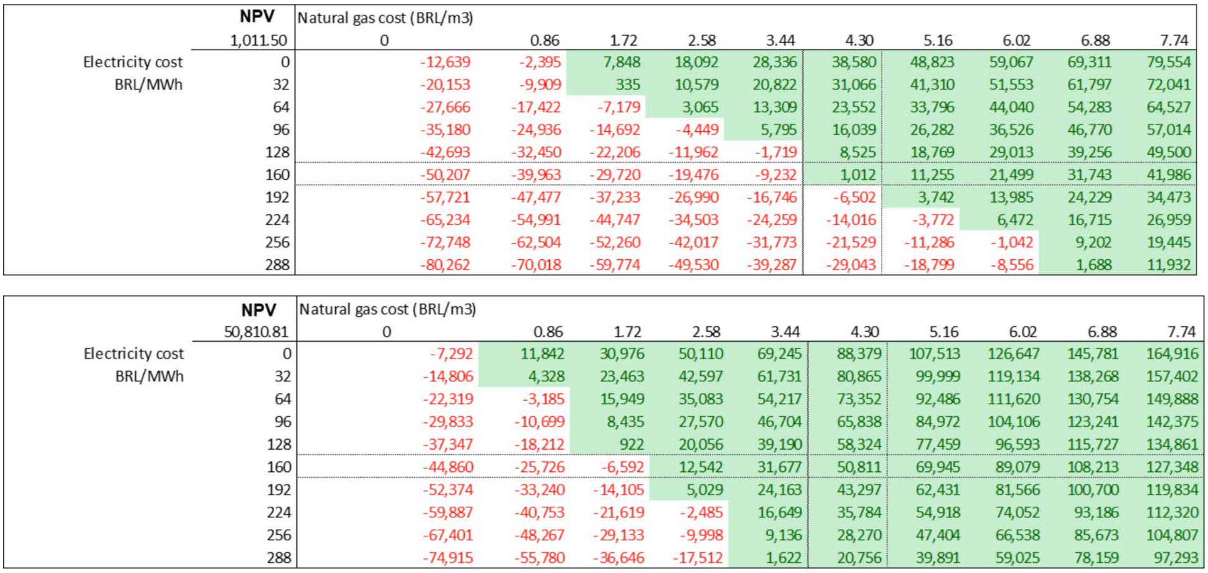
With a lesser impact, the electrolyzer cost is also relevant. Therefore, it is emphasized that the sector can seek financing sources for capital goods to mitigate the CAPEX burden, based on the decarbonization goal pursued by both industrial agents and government bodies. Proper project structuring for electrolysis, with the support of existing credit lines, may be a more appropriate short-term alternative, rather than waiting for the effect of economies of scale over electrolysis technology.

Based on the results above, the sensitivity analysis of the NPV with the costs of natural gas and electricity was reproduced for the base and promising scenarios, considering an electricity cost of 160 BRL/MWh and a 50% reduction in the electrolyzer CAPEX (3,632 BRL/kW) as a new reference level. It is important to note that these references are supported by the perspectives of the excess supply of renewable electricity in Brazil (Brasil Energia, 2024) and current electrolyzer cost levels (BloombergNEF, 2024).

Figure 7 shows the results of this analysis, demonstrating that the reduction in these two variables favors the project's viability. In the new reference case, a positive NPV of 1.0 million BRL was found for the base scenario, without considering the value of O2. In the context of an increase in the cost of natural gas, the project remains viable. In the promising scenario, which takes into account the use of O2, the NPV of the new reference is 50 million BRL. Furthermore, the project remains viable even with highly competitive natural gas prices, as low as R$ 0.86/m3.

Finally, the evaluated scenario supports the result regarding the importance of low electricity costs and electrolyzer CAPEX. In particular, the consideration of the value of O2 presents a relevant potential to mitigate the cost of hydrogen production.

Figure 7 – Sensitivity analysis for the base scenario (top) and promising scenario (bottom) under the new reference



	NPV	Natural gas cost (BRL/m3)									
	1,011.50	0	0.86	1.72	2.58	3.44	4.30	5.16	6.02	6.88	7.74
Electricity cost	0	-12,639	-2,395	7,848	18,092	28,336	38,580	48,823	59,067	69,311	79,554
BRL/MWh	32	-20,153	-9,909	335	10,579	20,822	31,066	41,310	51,553	61,797	72,041
	64	-27,666	-17,422	-7,179	3,065	13,309	23,552	33,796	44,040	54,283	64,527
	96	-35,180	-24,936	-14,692	-4,449	5,795	16,039	26,282	36,526	46,770	57,014
	128	-42,693	-32,450	-22,206	-11,962	-1,719	8,525	18,769	29,013	39,256	49,500
	160	-50,207	-39,963	-29,720	-19,476	-9,232	1,012	11,255	21,499	31,743	41,986
	192	-57,721	-47,477	-37,233	-26,990	-16,746	-6,502	3,742	13,985	24,229	34,473
	224	-65,234	-54,991	-44,747	-34,503	-24,259	-14,016	-3,772	6,472	16,715	26,959
	256	-72,748	-62,504	-52,260	-42,017	-31,773	-21,529	-11,286	-1,042	9,202	19,445
	288	-80,262	-70,018	-59,774	-49,530	-39,287	-29,043	-18,799	-8,556	1,688	11,932

	NPV	Natural gas cost (BRL/m3)									
	50,810.81	0	0.86	1.72	2.58	3.44	4.30	5.16	6.02	6.88	7.74
Electricity cost	0	-7,292	11,842	30,976	50,110	69,245	88,379	107,513	126,647	145,781	164,916
BRL/MWh	32	-14,806	4,328	23,463	42,597	61,731	80,865	99,999	119,134	138,268	157,402
	64	-22,319	-3,185	15,949	35,083	54,217	73,352	92,486	111,620	130,754	149,888
	96	-29,833	-10,699	8,435	27,570	46,704	65,838	84,972	104,106	123,241	142,375
	128	-37,347	-18,212	922	20,056	39,190	58,324	77,459	96,593	115,727	134,861
	160	-44,860	-25,726	-6,592	12,542	31,677	50,811	69,945	89,079	108,213	127,348
	192	-52,374	-33,240	-14,105	5,029	24,163	43,297	62,431	81,566	100,700	119,834
	224	-59,887	-40,753	-21,619	-2,485	16,649	35,784	54,918	74,052	93,186	112,320
	256	-67,401	-48,267	-29,133	-9,998	9,136	28,270	47,404	66,538	85,673	104,807
	288	-74,915	-55,780	-36,646	-17,512	1,622	20,756	39,891	59,025	78,159	97,293

Note: the new references are R$160/MWh for electricity cost and R$3,632/kW for the electrolyzer CAPEX. Other parameters are constant as in Table 1. Values in green highlight that the scenario results in a positive NPV.

Source: elaborated by the authors with the tool in CNI (2024)

4. CONCLUSION

The case study conducted with a ceramics industry company demonstrates the potential for hydrogen production at costs between 2.84 and 5.56 USD/kg H2. The modeled incremental cash flows were unattractive and misaligned (NPV lesser than 0) with the technical-economic risk in the current context established with the company. By breaking down the LCOH, the main contributors identified in this metric composition were the CAPEX, electricity cost, and O2 valuation. In sum, the hydrogen production project for partial natural gas replacement is only viable if the potential value of the oxygen (O2) co-produced in electrolysis is fully exploited, which can be achieved through oxygen-enriched combustion (OEC) or commercialization with third parties. Besides, the sector must be able to value avoided emissions at 250 BRL/t CO2. However, since the analysis does not account for O2 processing costs and equipment adaptation, it remains essential to seek electricity contracts at more competitive costs or to pursue well-structured distributed generation or self-production projects with renewable sources to facilitate the feasibility of the project in the long term. As indicated by the sensitivity analysis, combining incentives for the electrolyzer investments (halving the CAPEX) with oxygen appraisal can enable the decarbonization project with electricity prices as high as 288 BRL/MWh. Additionally, access to low-cost credit lines could be provided to the sector as a way to achieve decarbonization goals for the industry. Overall, the ceramic industry company can invest in the green hydrogen project with reasonability and consider it an effective decarbonization strategy if one of the tracked technical-economic contexts in the sensitivity analysis can be fulfilled.

It is further emphasized that the results obtained from the case study with the ceramics industry provide both quantification and an understanding of the potential value for other industrial subsectors regarding the potential for green hydrogen to enter their energy matrices, without overlooking the economic aspects within the energy transition agenda. The critical role of capital costs associated with electrolysis technology and electricity in supporting the process viability is highlighted, as well as the importance of valuing O2 recovery in cases where the hydrogen produced by electrolysis is close to its end-use, as shown in the breakdown of the LCOH. Future studies in this area can be expanded to other industrial sectors and applications involving hydrogen or derivative products, in order to explore technical and economic viability scenarios and guide public policies towards the development of financing programs or tax exemptions for decarbonization projects.

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