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INTEGRATING HYDROGEN INTO THE ENERGY MATRIX: A STRATEGIC ANALYSIS FOR SUSTAINABLE PLANNING IN MINAS GERAIS

Douglas Silva de Oliveira, Antonella L. Costa, Carlos E. Velasquez, Maria L. S. Gonçalves

Departamento de Engenharia Nuclear, Escola de Engenharia
Universidade Federal de Minas Gerais - UFMG,
Av. Antônio Carlos 6627, CEP 31270-901 Bloco 4, Belo Horizonte – MG

douglasilva.olv@gmail.com, antonella@nuclear.ufmg.br, carlosvelcab@nuclear.ufmg.br,
maria.lu.goncalvess@gmail.com

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ABSTRACT

This article addresses the urgent global need to shift away from fossil fuels towards cleaner energy sources, aligning with the transition to a low-carbon economy. It underscores hydrogen as a highly promising alternative due to its potential to significantly reduce greenhouse gases (GHG) emissions. With increasing investments and research aimed at improving its economic viability, various methods of hydrogen production are available, forming what is known as the "hydrogen rainbow". Green hydrogen, produced through water electrolysis powered by renewable energy sources (RES), emerges as a leading candidate for achieving a low-carbon economy. However, effective storage and transportation methods are crucial for determining the final cost and competitiveness of hydrogen. As countries strive for a low-carbon future, continuous research and development efforts are underway to enhance hydrogen's competitiveness compared to fossil fuels. The geographical focus on Minas Gerais is motivated by its abundant solar energy resources, offering a prime opportunity for green hydrogen production. Through planning and strategic execution, the study aims to construct a comprehensive hydrogen supply chain in Minas Gerais, integrating infrastructure development for renewable energy installations and the hydrogen route. Leveraging simulations conducted using HOMER Pro software, which bring economic optimization and efficient integration of solar and wind systems for hydrogen production, the study seeks to optimize the economic viability of green hydrogen projects by quantifying the economic benefits and environmental impacts, thereby providing actionable insights for decision-making towards a sustainable energy transition. After evaluating the wind and solar potential of the state, it became evident that solar power holds greater potential compared to wind power. As a result, the projects outlined in the article prioritize the production of green hydrogen using solar energy. By showcasing multiple economically viable projects designed to replace fossil fuels across various societal sectors, the article highlights the significant potential of green hydrogen production in Minas Gerais. Leveraging the state's abundant solar resources and optimized project designs generated through software, these initiatives aim to address the growing demand for clean energy while mitigating environmental impact.

1. INTRODUCTION

Since the industrial revolution, the increased exploitation and use of fossil fuels, due to antrophogenic activities, has caused a series of environmental impacts, such as global warming, air and water pollution, extreme weather events and the degradation of the ozone layer. As a result, there has been growing concern on the part of countries, which has resulted in the search for cleaner and more sustainable energy sources, driven by the urgency to mitigate these impacts. Thus, several global agreements were established, such as Montreal Protocol (1987), Eco-92 in Rio de Janeiro (1992), the UN Framework Convention on Climate Change (1992), the Kyoto Protocol (1997) and the most recent effort to mitigate climate problems was the Paris Agreement, signed at the 21st Conference of the Parties (COP21) in 2015, which aims to limit the increase in global temperature to 1.5ºC by 2050 [1]. Under this agreement, Brazil has committed to reducing its GHG emissions by 37% by 2025 and 43% by 2030, according to the official Nationally Determined Contributions (NDC) document delivered by the Brazilian government to the United Nations on September 21, 2016 [1]. However, in 2023, the country corrected its climate target by committing to reduce emissions by 48% by 2025 and 53% by 2030 [2].

To achieve a gradual transition away from fossil fuels and foster a cleaner, more sustainable economy, priority must be given to reducing their consumption, particularly in energy-intensive sectors like industry and transportation, which collectively account for 65% of Brazil's energy consumption. Despite this, renewable sources contribute only 21% and 62% to their respective energy shares, as per the 2023 Summary Report of the National Energy Balance [3]. Since 2003, when the country joined the International Partnership for Hydrogen and the International Partnership for Hydrogen and Fuel Cells (IPHE) [4], Brazil has hosted international conferences in recent years focusing on the subject of hydrogen energy. In this way, the country has shown interest in developing hydrogen for a long time, through feasibility studies on the insertion of hydrogen into the energy matrix. In this context, hydrogen has emerged as a promising alternative due to its ability to be produced from renewable sources and its emission-free combustion process, yielding water vapor instead of CO_2 emissions. While hydrogen offers multifaceted utility across various sectors, challenges remain in its integration into the energy landscape.

This article seeks to delve into potential solutions and offer pertinent data to ease the transition from fossil fuels to low-emission alternatives. Through a focused case study on Minas Gerais, the aim is to evaluate the potential of green hydrogen in the state. The goal is to validate the ongoing energy transition efforts and pave the way for the replacement of fossil fuels with environmentally friendly alternatives.

2. METHODOLOGY

The methodology adopted in this study takes an approach to transitioning Minas Gerais towards green hydrogen as a sustainable energy solution. It begins by identifying sectors heavily dependent on fossil fuels and analyzing their consumption patterns. Subsequent steps involve evaluating hydrogen technologies to determine their suitability as fossil fuel replacements and estimating the hydrogen quantity needed to meet current energy demands. Additionally, wind and solar potentials across Minas Gerais are assessed to identify optimal locations for renewable-powered hydrogen production facilities, with a focus on decentralized plants. Scenarios are then developed and simulated using HOMER Pro software, which is often used for optimizing microgrid designs and conducting economic analyses [5]. The research involves modeling systems that integrate renewable energy sources and electrolyzers for hydrogen production, with standardized parameters for consistency, as shown in section 2.1.

2.1 Modeling Assumptions for Homer Pro Projects

The primary assumptions for the projects are outlined through key parameters integrated into HOMER Pro simulations. Capital costs represent the initial purchase price of equipment, measured in US dollars per kilowatt (UUS$/kW). Replacement costs, equivalent to capital costs, cover equipment failures. Operation and maintenance (O&M) costs, representing ongoing expenses, are set at 5% of the capital cost, as per J. Hinkley's study [6]. Specific models used include LONGi LR6-60PE solar panels (US$175.70, US$8.78 O&M annually), PEM electrolyzers (US$1750 per kW, US$87.50 O&M annually), and Type IV hydrogen tanks

(US$633 per kg, US$31.65 O&M annually).The references provided indicate the sources from which the equipment models and associated costs were derived: [7] for solar panels, [8] for hydrogen tanks and [9] for electrolyzers.

Beyond equipment-related parameters, several economic factors are also crucial. The discount rate, representing the interest rate charged by the Federal Reserve to financial institutions for short-term loans, is assumed to be 8% due to the typically low borrowing rates accessible to municipal town halls [10]. The inflation rate is estimated at 4%, based on the Central Bank of Brazil's Focus Market Report [11]. The annual capacity shortage, capped at a maximum of 5%, follows the Ten-Year Energy Expansion Plan 2032 [12]. Lastly, the project lifespan is set at 20 years, aligning with the typical lifespan of solar panels used for hydrogen generation.

2.2 Sectors and consumption patterns

The methodology initiates by identifying sectors reliant on fossil fuels with potential for transitioning to green hydrogen, employing Hydrogen Power, Transportation, Storage, and Utilization (HPTSU) technologies [13]. Brazil's energy consumption landscape underscores hydrogen's significant potential across key sectors, encompassing residential, industrial, and transportation domains. Therefore, an analysis integration of hydrogen into the Minas Gerais scenario of these sectors will be carried out. Beginning with the residential sector, hydrogen emerges as a green alternative to liquefied petroleum gas (LPG) for heating, leading to notable reductions in GHG emissions. Data from the 2023 Energy Balance report from Minas Gerais reveals that LPG consumption was around 947,000 m³ in 2022 [3] and the GHG emission around 1,711,979 tCO_2e, according to the Greenhouse Gas Emissions Estimation System (SEEG in its Portuguese acronym) plataform [14].

Hydrogen has diverse industrial applications, particularly in steel production, where it can replace conventional fuels such as coke, coke-oven gas, natural gas, and coal. According to O. Paolone [15], this substitution can lead to significant emissions reductions. In Minas Gerais, a major steel-producing region, integrating hydrogen into the iron, steel, and ferroalloy sectors offers immense potential. These sectors consume approximately 3,635 million tons of oil equivalent (TOE) of primary energy annually, generating 14.9 million tons of CO2e (SEEG estimative). Steel production processes in the state use around 8,595 million m³ of coke-oven gas, 3,178 million tons of coal coke, and 4,689 million m³ of natural gas annually.

In the chemical industry, hydrogen is also a key player, particularly in ammonia production. Green hydrogen offers a pathway to decarbonizing the traditional Haber-Bosch (H-B) process, which currently relies on fossil-fuel-derived hydrogen [16]. As of 2018, synthetic nitrogen fertilizers contributed approximately 2.1% of global GHG emissions [17]. By utilizing renewable electricity and electrolyzers to produce hydrogen and sourcing nitrogen from the air, the ammonia production process can shift towards producing "green ammonia." This not only reduces the carbon footprint of fertilizer production but also opens up possibilities for broader applications, including use in shipping fuel and energy markets, where green ammonia could contribute significantly to decarbonization efforts.

The transportation sector also presents opportunities for hydrogen integration, with hydrogen fuel cells offering a cleaner energy alternative to conventional combustion engine vehicles [13]. According to IBGE [18], Minas Gerais has the second largest vehicle fleet in Brazil. In 2022, the passenger transport sector in Minas Gerais was responsible for emitting 9.6 million tons of CO2e, as recorded by SEEG. Hydrogen has the potential to reduce these emissions significantly. A study by Da Silva e Silva [19], which proposed electrifying urban bus fleets, found that diesel buses consume approximately 19.1 MJ/km, more than three times the 6.1 MJ/km consumed by electric buses. This highlights the benefits of hydrogen integration into the transportation sector, where it could play a critical role in reducing operational energy consumption and emissions.

2.3 Total Hydrogen demand by sector

The next step in the methodology quantifies the hydrogen volume needed to replace fossil fuels in Minas Gerais' energy transition. This is done by calculating the energy equivalence between the region's fossil fuel consumption, as detailed in the Minas Gerais energy balance, and hydrogen's lower calorific value of 120 MJ/kg [20]. Other fuels' lower calorific values used in the comparison include LPG (47 MJ/kg), coal coke (29 MJ/kg), and natural gas (47 MJ/kg, with 1 m³ of gas weighing 0.76 kg) [21] [22].

For the residential and industrial sectors, total energy consumption (in MJ) is divided by hydrogen's energy content (120 MJ/kg) to determine the hydrogen equivalent. In the transport sector, the focus is on replacing Belo Horizonte's BRT MOVE bus fleet, which accounts for 16% of the city's total bus mileage, approximately 478,000 km per month [23]. The hydrogen demand calculations for all sectors are summarized in Table 1.

Hydrogen demand estimates are based on total LPG consumption in Minas Gerais, even though a large portion of LPG is used for cooking, not heating. The National Energy Balance (BEN) indicates that roughly half of the final energy consumption in residential sectors is for cooking, suggesting that hydrogen demand calculated for LPG replacement may exceed actual needs. However, excess hydrogen could be repurposed for other sectors, ensuring optimal resource utilization.

Tab. 1. Total Hydrogen Quantity for Substitution the fossil fuels demand in the sectors.

Type of Substitution	Total Energy (MJ/year)	Total Hydrogen (kg/year)
Natural Gas to hydrogen for Heating	167,503,939	1,395,866
Coal coke to hydrogen in reduction process	90,282,691	752,356
Coke-oven to hydrogen in reduction process	167,614,200	1,396,785
LPG to hydrogen for heat in residential sector	36,364,800	303,400
Diesel to hydrogen in the transport sector	109,557,600	912,980
Sum of Total Hydrogen (kg/year)		**4,761,387**

For this research, the industrial sector in nine municipalities was studied using data from the Brazilian Steel Institute [24], which lists nine major steel production parks in various cities across Minas Gerais. To determine hydrogen requirements, the proportion of steel production for each municipality, based on the Institute's data, was calculated. For instance, Aperam South America in Timóteo contributes 9.2% of Minas Gerais' total iron production of 9,803,000 tons [25], requiring about 331,821 kg of hydrogen annually. This methodology was uniformly applied to all municipalities, with results detailed in Tab. 2. The data for the other municipalities were taken from the following references: [26] - [31]. It is possible to note that the sum of total hydrogen required in Tab. 2 is much larger than the sum in Tab. 1. This is due to some projects in the industrial sector that are scheduled to begin in 2023 and 2024 and, then they have not been considered for this study.

Tab. 2. Total amount of hydrogen per municipality for industrial demand.

Municipality/Company	Total Hydrogen (kg/year)	Municipality/Company	Total Hydrogen (kg/year)
Timóteo/Aperam South America	331,821	Ouro Branco/Gerdau	2,023,387
Juiz de Fora/ArcelorMittal	403,956	Ipatinga/Usiminas	1,168,587
Monlevade/ ArcelorMittal	811,519	Jeceaba/Vallourec	367,888
Barão de Cocais/Gerdau	122,630	-	-
Sum of Total Hydrogen (kg/year)		**5,229,788**	

According to a report from G1 [32], Brazil's annual production of ammonium nitrate (NH_4NO_3) reaches only 500,000 tons, which is significantly lower than the country's demand. Consequently, Brazil imports approximately 1.2 million tons of ammonium nitrate each year. To meet the total annual consumption of around 1.7 million tons—which comprises both the domestically produced 500,000 tons and the 1.2 million tons imported—approximately 361,250 tons of ammonia (NH_3) are required. This estimation is based on the stoichiometric relationship between ammonia and ammonium nitrate in the synthesis reaction. Each ton of ammonium nitrate necessitates approximately 0.2125 tons of ammonia [33].

To produce this quantity of ammonia via the Haber-Bosch process, which synthesizes ammonia from hydrogen (H_2) and nitrogen (N_2), around 64,000 tons of hydrogen would be needed, given that 177 kg of hydrogen are required to generate one ton of ammonia [34]. To identify a suitable location for a hydrogen power plant aimed at ammonia production in Minas Gerais, we can reference Petrobras's plan to establish a facility in Uberaba capable of producing approximately 519,000 tons of ammonia annually in 2014 [35]. However, this project did not progress. For this study, we will consider Uberaba as a potential site for the installation of a hydrogen plant that will meet the country's demand for ammonia and, consequently, ammonium nitrate.

2.4 Solar and Wind potentials

The third step of the methodology involves identifying solar and wind potential in Minas Gerais, which will be accomplished using Energy Data Info [36], an open data platform designed for renewable energy assessments. This platform, supporting Sustainable Development Goal 7, offers access to renewable energy data for diverse stakeholders. The map in Fig. 1 shows some of the cities in Minas Gerais selected for the simulations in this paper and highlighting the north-northwest areas with the highest solar potential, around 1,500 kWh/KWp. Additional potential exists in central and west-central regions. This data corroborates findings from a CEMIG study [37], confirming the northern region's solar energy generation potential in Minas Gerais.

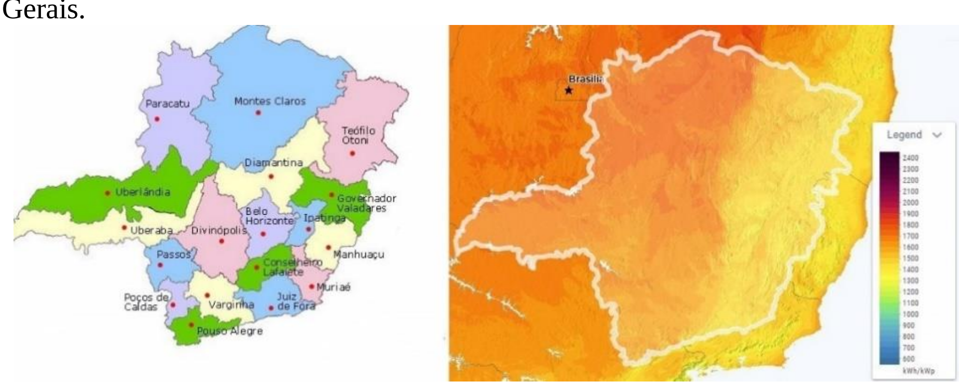

Fig. 1. Minas Gerais's division of the state by the main municipalities and solar potential. Adapted image from [37] and [38].

Accessing the wind atlas via the Energy Data Info platform reveals that Minas Gerais has modest wind potential, primarily in central and northern regions near Belo Horizonte, Diamantina, and Montes Claros. Areas around Governador Valadares, Teófilo Otoni, and Diamantina show potential, especially for 200-meter towers with an average density nearing 1000 W/m². However, the annual average wind speed is about 5.2 m/s, which is below the minimum required for typical wind turbines. Consequently, wind power generation is not considered economically viable in this study.

2.5 Design the Projects for simulations

The projects will include two fundamental systems: a photovoltaic (PV) setup for hydrogen production via electrolysis, capturing solar energy with solar panels, and a wind system for hydrogen production through electrolysis, utilizing energy from a wind turbine. In HOMER Pro software, incorporating a load in the system is essential, which will be configured as hydrogen demand tailored to each project's requirements. Fig. 2 illustrates an example of a solar system project constructed in HOMER Pro.

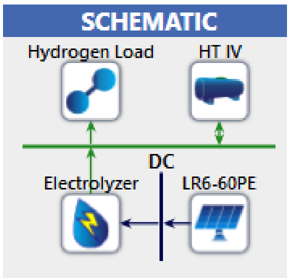

Fig. 2 Example of a schematic built in HOMER Pro. Image taken from a personal project.

3. RESULTS AND DISCUSSIONS

This section presents the results of optimized scenarios generated in HOMER Pro, highlighting the dominance of solar-based systems for green hydrogen production in Minas Gerais. The region's wind potential is limited and not as economically viable as its solar potential. Simulations focus on solar systems due to their lower total project costs and levelized hydrogen costs (LCOH), measured in US$/kg of hydrogen, compared to wind systems. Beginning with the residential sector, Tab. 3 illustrates all the optimized scenarios derived from the software, tailored to each municipality's demand for replacing LPG for heating purposes.

Tab. 3. Optimized scenarios built in HOMER Pro for residential demand.

PV-H2 PROJECTED SYSTEM											
Municipality	**H2 [kg/ano]**	**Project Cost [$]**	**Hydrogen Cost [$/kg]**	**Capacity of PV System [kW]**	**Number of solar panels**	**Municipality**	**H2 [kg/ano]**	**Project Cost [$]**	**Hydrogen Cost [$/kg]**	**Capacity of PV System [kW]**	**Number of solar panels**
Belo Horizonte	34,204	4,900,000	10.50	2,718	8,768	Poços de Caldas	2,419	370,605	11.10	199	642
Betim	6,083	899,209	10.60	447	1,442	Varginha	2,016	333,440	11.10	179	577
Nova Lima	1,650	262,040	10.50	145	468	Pouso Alegre	2,248	371,971	11.40	196	632
Diamantina	705	106,789	10.70	53	171	Juiz de Fora	7,988	1,260,000	11.40	724	2,335
Montes Claros	6,119	901,637	10.60	448	1,445	Ipatinga	3,364	540,428	11.60	286	923
Paracatu	1,389	213,146	10.70	120	387	Teófilo Otoni	2,030	317,443	11.30	171	552
Uberlândia	10,535	1,550,000	10.70	886	2,858	Muriaé	1,538	259,480	11.80	145	468
Uberaba	4,990	753,423	10.80	419	1,352	Governador Valadares	3,799	535,727	11.50	283	913
Passos	1,653	250,507	10.90	141	455	Manhuaçu	1,357	218,770	11.50	123	397
Divinópolis	3,413	522,157	11.00	281	906	Conselheiro Lafaiete	1,944	300,839	11.10	163	526

In Belo Horizonte city, the capital of Minas Gerais, a detailed analysis identifies a suitable location for a solar farm, projected to cover approximately 15,800 m² in HOMER Pro. This park is expected to host 9,535 solar panels, alongside other PV-H_2 system components like the electrolyzer and battery. One potential site for this solar park is the Presidente Tancredo Neves

Administrative City, spanning 804,000 m², with only 17,000 m² built-up [40]. An Optimal place for the solar panels could be in the existing building rooftops within the Administrative City. Alternatively, undeveloped areas of the complex could house components like the electrolyzer and battery, utilizing available land without interrupting ongoing activities. Analysis of scenarios generated by projects in HOMER Pro indicates relatively low construction costs for solar plants and green hydrogen production to replace LPG for home heating. With a potential lifespan of up to 25 years, these projects offer long-term sustainability, requiring replacement only if equipment becomes damaged or reaches the end of its useful life. Considering the estimate emissions for green hydrogen production around 3 $kgCO_2e/kgH_2$, following in the existing projects around the world, as cited in the World Economic Forum article [41], the total emissions for the hydrogen demand in the residential sector will be near 802,000 tCO_2e, a low volume of emissions, in contrast with the almost 2 million tons of CO_2e emitted in 2022. Thus, the transition to hydrogen in the residential sector could mitigate 47% of the state's current CO_2 emissions. This transition serves as a crucial model for other states, contributing to broader regional and national reductions in GHG emissions.

Continuing with the results, it is observed that the industrial steel, iron, and ferroalloy sector displayed notably higher project prices compared to residential projects. This disparity arises from the substantially higher demand for hydrogen in the metallurgical industrial sector, necessitating the acquisition of larger equipment to meet this demand. Tab. 4 offer an overview of the key values calculated and optimized by the software.

Tab. 4. Optimized scenarios built in HOMER Pro for industrial demand.

Municipality	H2 [kg/year]	Project Cost [$]	Hydrogen Cost [$/kg]	Capacity of PV System [kW]	Number of solar panels
Ouro Branco	2,023,387	312,000,000	11.20	167,048	538,865
Ipatinga	1,168,587	183,000,000	11.40	105,350	339,839
Monlevade	811,519	122,000,000	11.00	65,448	211,123
Juiz de Fora	403,956	63,500,000	11.40	36,519	117,803
Timóteo	331,821	52,000,000	11.40	29,945	96,597
Jeceaba	367,888	56,400,000	11.20	30,986	99,955
Barão de Cocais	122,630	18,600,000	11.00	9,965	32,145

Furthermore, the simulation conducted in Uberaba to assess hydrogen supply for the ammonia industry led to the development of an optimized solar power plant project in HOMER Pro. The project has a total cost of US$9.2 billion, with an installed capacity of 5,297,175 kW, requiring approximately 17,087,661 solar panels (equivalent to around 28 million m²). The cost of hydrogen production was calculated at US$10.5 per kg, utilizing an electrolyzer with a capacity of 1,360,759 kW and a hydrogen storage tank with a total capacity of 200,000 kg. The capital expenditure (CAPEX) for the project is estimated at US$5.51 billion.

For comparison, the current price of ammonium nitrate stands at approximately US$228 per ton [42]. Considering that Brazil imports around 1.2 million tons of ammonium nitrate annually, over the 20-year lifespan of the proposed project, the total cost of imports would be around US$5.5 billion, aligning closely with the CAPEX of the proposed ammonia project. By transitioning to domestic fertilizer production, Brazil could significantly reduce its reliance on fluctuating global import prices. Moreover, integrating a hydrogen production facility with a solar power plant to enhance ammonia production presents a strategic advantage, promoting energy independence and sustainability for the country's agricultural sector.

The priority for the transportation sector is transitioning the BRT MOVE bus fleet to hydrogen fuel cell vehicles in Belo Horizonte, then the analysis performed using HOMER Pro, indicates a value of US$138,000,000, considering 20 years of project lifetime, with a levelized cost of hydrogen about US$10.90/kg. Based on the findings from the article referenced [43], it is noted that the lifespan of bus fleets in many countries exceeds 12 years, which is the replacement period observed in the USA. Therefore, to account for this variability conservatively, the proposed project will plan for a bus fleet replacement cycle of 10 years. This means that the capital expenditure for acquiring a new fleet of buses will need to be included every decade. According to the document [44], a fuel cell electric bus (FCEB) costs an average of 1 million dollars. So, considering the actual fleet of 425 buses, the cost of replacing the fleet every 10 years would be US$425 million. These figures are merely recommendations based on the software-optimized design and the prevailing conditions observed by the authors at the time of composition. Hence, if this project is executed under similar circumstances, the estimated total project cost stands at approximately US$1.1 billion, excluding the revenue from the initial bus fleet sales.

To conclude the analysis and discussion of the results, it is valuable to compare the costs of the hydrogen plant projects presented in this article with those of plants utilizing other energy sources. For this comparison, we can reference data from the 2022 Electricity ATB Technologies and Data Overview, produced by the National Renewable Energy Laboratory (NREL) [45], in conjunction with some of the data from the projects in this article. The capital expenditure (CAPEX) will be presented in US$/kW for each project. The NREL website provides both maximum and minimum values for various energy sources, assuming a project lifetime of 20 years, which aligns with the timeframes of the projects discussed in this paper. To simplify the comparison, the most expensive and least expensive hydrogen plant projects from this article will be selected to establish the maximum and minimum values for green hydrogen. Tab. 5 below presents the calculated and referenced values.

Tab. 5. CAPEX for different energy sources power plants. Adapted from [45].

Source	**CAPEX (US$/kW)**		**Source**	**CAPEX (US$/kW)**	
	Min	**Max**		**Min**	**Max**
Green Hydrogen for Residential Sector with Solar Energy	1,089	1,213	Geothermal	5,902	40,273
Green Hydrogen for Industrial Sector with Solar Energy	1,123	1,125	Nuclear	7,086	7,789
Green Hydrogen for Transportation Sector with Solar Energy	1,177	1,177	Offshore Wind	2,557	4,857
Green Hydrogen for Residential Sector with Wind Energy	7,557	29,857	Biopower	4,305	4,305
Green Hydrogen for Transportation Sector with Wind Energy	4,672	4,672	Hydropower	2,574	16,283
Commercial PV	1,302	1,373	Natural Gas	882	2,096
Residential PV	2,030	2,105	Coal	3,027	5,094

Considering the data presented in the table above, it is evident that the hydrogen projects discussed in this paper fall within an acceptable range of CAPEX values (in US$/kW) when compared to other energy sources, with the exception of wind energy projects for the residential sector, which is understandable given the relatively smaller wind potential in Minas Gerais, as well as the fact that a wind energy project usually requires a lot of investment and space. Moreover, with green hydrogen's low CO_2 emissions and possible good competitive cost on the market, hydrogen emerges as one of the most cost-effective energy sources among those analyzed, mainly by being competitive with commercial and residential solar panels, as well as being able to compete well with energy sources that emit a lot of GHG, such as coal and natural gas.

4. CONCLUSION

The projects and analyses outlined in this article underscore the potential viability of hydrogen as a compelling alternative in the transition toward a low-carbon economy. This is particularly evident in its capacity to replace fossil fuels across industrial, residential, and transportation sectors. The data presented in this paper has an insightful perspective on how the state of Minas Gerais could integrate hydrogen into its energy matrix, potentially sparking interest among other states and the nation as a whole in embracing hydrogen as a fossil fuel alternative. From a technical standpoint, green hydrogen emerges as a viable option for major sectors such as industry, transportation, and residential use, as delineated throughout this study. This feasibility stems from the fact that the projects and simulations presented can be readily implemented in Minas Gerais using existing technologies within the country.

Moreover, the projects are relatively cost-competitive, with CAPEX values ranging from 1,089 to 1,213 US$/kW for hydrogen power plants with solar energy, making it the third most affordable option, as shown in Tab. 5. Naturally, the cost estimates in this article accounted for specific interest rate conditions and used Homer Pro to optimize the project values. Nevertheless, this presents an attractive margin for considering investments in the integration of hydrogen into the energy matrix of Minas Gerais, and, in the long term, potentially for the entire country.

Drawing from the data cited in Section 2 of this paper, the total annual CO_2 emissions for these sectors amount to 26,487,673 tCO_2e. By introducing hydrogen to replace fossil fuels in these sectors, the potential reduction in GHG emissions would be approximately 14 million tCO_2e. This highlights the economic viability of hydrogen as a compelling alternative in the transition toward a low-carbon economy. This finding is underscored by the insightful perspective on how the state of Minas Gerais could integrate hydrogen into its energy matrix, as outlined in the projects and analyses presented in this article. From a technical standpoint, green hydrogen emerges as a feasible option for major sectors such as industry, transportation, and residential use, given the readily implementable nature of the projects and simulations using existing technologies within the country. This potential integration of hydrogen in Minas Gerais could spark interest among other states and the nation as a whole in embracing hydrogen as a fossil fuel alternative.

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