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GREEN HYDROGEN PRODUCTION THROUGH THE ELECTROLYSIS PROCESS AND ITS POTENTIAL IN BRAZIL

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Abstract. *This study considers the production of hydrogen in Brazil through water electrolysis using renewable energy sources, namely solar, wind, and hydropower. The study aims to establish a correlation between the country's green hydrogen production capacity and the fossil fuel consumption aiming the transportation sector. The findings reveal that a transition to hydrogen-powered vehicles in Brazil would require approximately 6.3 billion kilograms of hydrogen per year, which is six times the current national production. Meeting this demand would require a significant increase in renewable energy production, with approximately 60 % of Brazil's renewable energy grid (excluding biomass) required for hydrogen production. However, directing such a substantial portion of the renewable energy grid exclusively towards hydrogen production presents challenges and may not be economically viable. Nonetheless, the study proposes a favorable future scenario by gradually expanding the fleet and renewable hydrogen production in line with Brazil's renewable energy growth, which would require a 1.4% increase in photovoltaic, wind power, and hydropower combined capacity over 10 years to accommodate the additional hydrogen-powered vehicles.*

Keywords: *green hydrogen, electrolysis, Brazil, vehicle fleet*

1. INTRODUCTION

World's energy consumption grows annually, exceeding 595 EJ in 2021, representing the highest consumption growth in history. Despite of the efforts to promote the proliferation of renewable energy sources, roughly 80% of the energy consumed is still categorized as non-renewable (BP, 2022). Concerned with the environment impact associated with the use fossil fuels, several countries have invested in clean energy technologies, which has yielded to a marginal rise of merely 0.9% (321 Mt) in atmospheric CO₂ emissions in 2022. This value is lower than the increase of previous years. (IEA, 2023). As widely known, clean energy can be obtained, for example, through wind, geothermal, nuclear, solar, hydroelectric, ocean thermal, and tidal systems (Dincer and Zamfirescu, 2012). However, the choice of the deployment site for renewable energy systems aiming to achieve the highest energy production yield, must take into consideration the local environmental characteristics.

Additionally, and within the context above, certain energy consuming sectors also have their own specificities. For instance, another significant source of CO₂ emissions is the transport sector. Currently, 1 liter of gasoline emits 2.28 kg of CO₂ (Carvalho, 2011); the vast majority of the world's vehicle fleet is still powered by internal combustion engines. Nevertheless, it is vital to seek sustainable solutions to reduce fossil fuel dependence and lower emissions. In this scenario, using a fuel with minimal environmental impact, such as green hydrogen, is a promising alternative. For instance, hydrogen has several characteristics that favor its use in applications within the transportation section. For example, the hydrogen/air mixture is ignited with a fraction of the energy needed by a gasoline-air mixture (Gao *et al.*, 2022). Furthermore, the only by-product generated by hydrogen combustion is water vapor (Sdanghi *et al.*, 2020), which represents a significant advantage in reducing emissions.

According to the International Energy Agency (IEA), roughly 94 million tons (Mt) of hydrogen were produced in 2021. However, low or zero-emission hydrogen production (green hydrogen) represents less than 1% of this value. The remaining portion refers to gray hydrogen production, which is derived from fossil fuels and is responsible for over 900 Mt of CO₂ emissions (IEA, 2022). Therefore, there is a clear need to develop and optimize processes and systems capable of producing green hydrogen efficiently.

While there are several well established non-renewable hydrogen production processes (Ma *et al.*, 2019), arguably the best alternative for producing the so-called green hydrogen is electrolysis, (Hulteberg and Karlsson, 2009). In this case, green hydrogen, which is produced by powering the electrolyze with a renewable energy source, is a physico-chemical process that uses electrical energy from a source to stimulate a chemical reaction in a medium, producing hydrogen and oxygen. The three commercially widespread technologies include proton exchange membrane electrolysis (PEM), solid oxide electrolysis (SOEL), and alkaline water electrolysis (AWE) (Brauns and Turek, 2020). The latter is

cheaper and its components have a larger lifespan when compared to the others. Although the installed power for hydrogen production from alkaline electrolysis represents a small portion of the world's energy grid, its development increases the flexibility of sustainable sources, reduces greenhouse effects, and contributes to the economic expansion of the installation location.

In order to increase the contribution of hydrogen utilization in the national grid energy, Brazil has great potential, as green hydrogen finds in the country abundant renewable energy from hydroelectric power plants, solar panels and wind farms. In 2022, the Brazilian electrical grid reached a renewable share of 78.1%, with hydroelectric power accounting for 57% alone (EPE, 2022). Additionally, there is an excellent opportunity for the utilization of hydrogen in automotive vehicles despite the existing challenges, which require, for example, the development of efficient/safe storage, transportation and distribution systems. Once these challenges are overcome, Brazil has great potential to be one of the pioneers in this automotive sector, considering that the country was the 6th largest automotive market in the world in 2022 (Munoz, 2023).

1.1 Renewable Energies

The renewable energy processes producing electricity with the highest yields and contributions to the power grid are found in photovoltaic (PV), wind, and hydropower. PV energy is obtained through the photovoltaic effect, which involves the direct conversion of light into electricity (Nascimento, 2004). This conversion is promoted by PV cells composed of layers of distinct materials and connected through an external conductor. Therefore, and as long as there is irradiance incidence on the cell, there will be electric current, with its intensity varying with the intensity of the incident irradiance. In an ideal scenario, this assembly of PV cells, which are connected as a serial circuit, results in a PV module that generates a direct current (DC) having a conversion efficiency of up to 25 % (Glunz *et al.*, 2015).

Wind power was arguably underutilized before the 21st century, however, by 2011, power capacities in the megawatt range had already been achieved (Ferreira, 2011). The process, which is well understood, converts kinetic into mechanical energy capable of powering a generator (Resende, 2011). The systems responsible for this energy conversion are the wind turbines, which, in a simplified manner, consist of a tower and rotor, with the latter being connected to a generator through a shaft. However, due to the number of components and associated losses, only 25% of the available wind energy is effectively delivered to the grid (Castro *et al.*, 2010).

Hydropower generation occurs through the operation of a hydropower plant, which harnesses the hydraulic potential of water stored in a reservoir, converting energy from potential to mechanical within a turbine, and mechanical into electrical in a generator (Caus, 2014). There are several losses related to the above-mentioned energy conversion processes. For instance, in the turbine, the efficiency ranges from 88% to 96% due to the internal and external losses, such as friction (Encina, 2006). Similarly, in the generator, losses occur in several locations and subsystems, and as a result, the generator's efficiency varies between 90% and 99%.

1.2 Hydrogen

The hydrogen economy was conceived only in the first half of the 1970s, coinciding with the end of the mechanization era, where coal was the primary energy resource, and the beginning of electrification, where oil was the primary resource for energy generation (Winter, 2009). Since then, the characteristics of hydrogen have been specified for its use as replacement for fossil fuels. The properties of hydrogen are depicted in Table 1, alongside the ones for the gasoline. Due to its properties, hydrogen has been widely used in numerous applications, including ammonia production, hydrogenation of petroleum sub products, among others (Karagöz and Köten, 2019). While these applications are well established, the use of hydrogen as a fuel is more recent.

Among the many features that make hydrogen an interesting source of energy, it is important to mention that hydrogen possess a very highest gravimetric energy density if compared to other fuels (Aziz *et al.*, 2019) being approximately three times higher than that of gasoline (see Table 1). On the other hand, when considering the volumetric densities and, consequently, the volumetric energy density of the two compounds at standard temperature and pressure, hydrogen is significantly lower than gasoline (Sdanghi *et al.*, 2020). Therefore, one of the main difficulties associated with the commercial viability of hydrogen as a fuel lies in its storage, as it needs to be pressurized up to 70 MPa to ensure optimal performance (Toyota, 2023). Additionally, the lower and upper flammable limits of hydrogen highlight the possibility of hazardous situations, as the combustion range spans from 4% to 75% of the available gas volume in the environment.

From an environmental standpoint, the products of hydrogen's combustion are water and heat, making it a desirable fuel candidate when considering decarbonization of transportation sector (Hall *et al.*, 2014). However, there are technical challenges associated with its production, transport and storage. For instance, it is estimated that the hydrogen production cost through electrolysis is several times that of gasoline.

Table 1. Comparison of hydrogen and gasoline properties (Sdanghi *et al.*, 2020), (GlobalPetrolPrices, 2023), (Clean Hydrogen JU, 2022).

Property	Hydrogen (H ₂)	Gasoline
Gravimetric energy density, (MJ/kg)	144	46.8
Density (298 K and 1 atm), (kg/m ³)	0.089	775
Volumetric energy density, (MJ/m ³)	12.8	36270
Laminar flame speed, (m/s)	2.65-3.25	0.44
Flammable limits (lower-upper), (vol%)	4-75	1.4-7.6
Pump price in USA, (USD/kg)	4-8 (Electrolysis)	1.42

This cost discrepancy may vary depending on the type of methodology employed for hydrogen production, with an emphasis on centralized and decentralized facilities (Lundblad *et al.*, 2023). The centralized method involves hydrogen production in large-scale industrial facilities, where it is compressed on-site and subsequently distributed to users. This centralized enables the provision of energy to large regions and ensures a better control of gas quality. However, it still faces significant disadvantages due to the subdivision of processes, especially in the stages of storage, transportation, and distribution. On the other hand, the second method encompasses small and medium-scale plants where all aspects related to hydrogen are handled locally (e.g. production and storage). However, this installation modality faces the challenge of providing a limited daily quantity of hydrogen and requires high initial investments.

1.3 Electrolysis

Amongst the most well-known approaches for green hydrogen production, water electrolysis stands out from the others due to its efficiency, technological maturity, scalability, low carbon emissions, and wide availability of resources (Ji and Wang, 2021). Water electrolysis is a well-developed technology that efficiently produces green hydrogen using water as a readily available and abundant feedstock. Furthermore, its adaptability to different production demands provides versatility, where it is possible, through the choice of electrolysis technology to be used, to achieve small to large-scale productions.

According to (Viola, 2015), the two most commercially used water electrolysis methods are the Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane Electrolysis (PEM). More information on these processes can be found in (Zhang *et al.*, 2016) and (Ayers, 2019), respectively. However, when it comes to renewable energy, the most efficient method is to combine PV modules with PEM electrolysis. The overall efficiency achieved in an ideal environment with direct solar-to-hydrogen conversion using this method is approximately 16% (Rzayeva *et al.*, 2001). This value is justified based on the efficiency of current PV cells coupled with the 75% efficiency of the PEM electrolyzer. In addition, (Joshi *et al.*, 2011) conducted a more detailed study in 2011 and concluded that the global efficiency for hydrogen production under real conditions, including electricity storage methods, is even lower, ranging from 4.53% to 5.62%.

For wind power applications, AWE electrolysis is better established in the market (Li *et al.*, 2022) due to its mature technology and lower cost compared to PEM electrolysis. With this system, it is possible to achieve an overall efficiency of 60% (Ntziachristos *et al.*, 2005). Unlike other renewable energy systems, wind energy-based systems do not solely rely on the environmental conditions to produce hydrogen. For instance, Gökçek demonstrated in 2010 that varying the turbine's distance from the ground can increase the amount of hydrogen produced by approximately 67%.

Lastly, due to the limited number of studies on the correlation between hydropower plants and the most suitable electrolyzer for hydrogen production, both PEM and AWE electrolyzers can be used. Moreover, surplus electricity generated is commonly used to produce hydrogen, which can possibly be stored for later use during high demand periods (Bamisile *et al.*, 2020).

1.4 Objectives

This study aims to estimate the necessary expansion in renewable energy production to replace/add a specific percentage of green hydrogen-powered cars in the Brazilian vehicle fleet. Considering the global interest in zero-emission vehicles and the urgency to reduce dependence on fossil fuels, the introduction of hydrogen-powered cars is a promising alternative. However, its viability depends on the sufficient availability of renewable energy to produce hydrogen. Data on energy consumption in the transportation sector, average hydrogen-to-electricity conversion efficiency, and renewable energy production capacities in Brazil were used to estimate the required expansion in renewable energy production. It was also projected the specific percentage increase that the Brazilian renewable energy grid, composed of sources such as PV, wind, and hydropower, would need to achieve in the next 10 years to meet the estimated demand for hydrogen-powered vehicles. This study aims to understand the challenges and opportunities of transitioning to a hydrogen-powered vehicle fleet in Brazil, provide insights for energy planning and decarbonization

policies in the transportation sector, and guide investments and initiatives to drive the country's sustainable development, resulting in significant reductions in greenhouse gas emissions.

2. METHODOLOGY

This section presents the methods to identify, based on the potential of renewable energy production, the Brazilian capacity for hydrogen production with the aim of adding/replacing hydrogen-powered vehicles to the current fleet. The energy required to supply 0 to 100% of the fleet with green hydrogen powered vehicles was analyzed in order to provide a future perspective of their growth, while relating it to the potential of Brazil's power grid.

2.1 Installed and Effective Production Capacity

The National Electric System Operator (ONS) manages the generation and distribution of the Brazilian electrical grid (ONS, 2023). Therefore, it has data regarding the installed energy capacity throughout Brazil from power plants classified under the following operation types of Type I, II-A, II-B, and II-C. In May of 2023, Brazil had an installed capacity of 1586.5 TWh, with over 79% distributed among hydroelectric (962 TWh), wind (216 TWh), and PV (77 TWh) energy sources. However, power plants cannot always generate energy according to their installed capacity due limitations (e.g., transmission). Therefore, the capacity factor, which represents the ratio between the energy effectively generated by power plants and the installed capacity, is used to oversee the plants' operation.

In this regard, the National Electric Energy Agency (ANEEL), which oversees the ONS, provides updated capacity factors for the three discussed renewable energy sources (ANEEL, 2023a). Among these, in May 2023, hydropower had the highest factor, reaching over 56% conversion, followed by wind turbines at 13%, and PV at 5%. The discrepant difference between the capacity factors of hydropower and photovoltaic energy is mainly due to the availability of rivers in Brazil, in contrast to the availability of solar radiation, where the country has regions with high irradiance, such as the Northeast, and regions with low irradiance, such as the southern region. Due to these factors, the useful energy produced in hydropower, wind, and photovoltaic power plants reached 578.9 TWh. This value was composed of 94.35% hydropower, 4.99% wind power, and 0.66% photovoltaic power.

2.2 Energy to Power a Hydrogen Car

The Ministry of Transport classifies vehicles into 21 categories, ranging from motorcycles to agricultural tractors (Ministry of Transportation, 2023). However, in order to analyze the population driving behavior in conjunction with the advancement of hydrogen utilization as a fuel, only light vehicles were selected to calculate the required amount of hydrogen production. According to KBB Brasil, light vehicles in Brazil typically travel around 12,900 kilometers per year (KBB, 2019).

The commonly used hydrogen car model is the Toyota Mirai LE, a model launched in 2022. This car features a fuel cell vehicle (FCV) for converting stored hydrogen into electricity, which is then used in the 134 kW synchronous AC motor. It also has a 311V lithium-ion battery and is only available at dealerships in California and Hawaii (FuelEconomy, 2022). The vehicle's city consumption corresponds to 119 km/kg of hydrogen, providing a range of 531 km per tank.

The hydrogen production required to meet the fleet annual mileage is calculated using the following expression,

$$M = \frac{F \times D}{C_{\text{city}}}, \quad (1)$$

where the M represents the quantity, in kg, of hydrogen to be produced, F represents the number of operating vehicles, D represents the number of km traveled per car in a given period of time, and C_{city} represents the vehicle's fuel consumption in the city, in this case, in km/kg.

As mentioned earlier, wind energy produces hydrogen with AWE system while PV uses a PEM; hydropower might use either. Additionally, it is necessary to consider that the losses during the conversion of renewable energy (water, wind, and solar) to electrical energy are neglected, as the useful power obtained through the capacity factor already results in the energy made available from the power plants to the grid, in this case, to the electrolyzers. Given this perspective, it becomes essential to perform a brief comparative analysis of the characteristics of AWE and PEM electrolyzers. The PEM electrolyzer, despite its ability to achieve hydrogen purities of up to 99.999%, is considered the more expensive of the two. As a result, the AWE electrolyzer has gained greater market adoption, including its capacity to produce significant volumes of hydrogen. Despite these differences, both systems exhibit efficiencies that vary approximately around 75%, as established by the following expression,

$$\eta = \frac{\text{HHV}_{\text{H}_2}}{\text{Electric energy consumption}}, \quad (2)$$

where HHV_{H_2} represents the higher heating value of 1 mole of hydrogen, a value of 40 kWh/kg was adopted (Clean Hydrogen JU, 2022). Finally, neglecting losses caused by fuel storage and the involved processes, the amount of energy required to fuel a fraction of the vehicle fleet composed of hydrogen-powered cars is given by the following expression,

$$\text{Required Energy} = \frac{M \times HHV_{H_2}}{\eta}, \quad (3)$$

2.3 Required Growth of Brazil's Power Grid

Needless to say that, much like hybrid and electric vehicles, the presence of hydrogen-powered vehicles in Brazil is still incipient (Ribeiro, 2023). Therefore, and in order to identify whether the Brazilian power grid could grow sufficiently to keep up with the growth of fuel cell vehicles, the projection provided by the Energy Research Company (EPE) for hybrid and electric cars between the period of 2023 and 2032 (EPE, 2023) was used as a reference. The share of each renewable energy source on the total value was kept identical to the year 2023, which allows a comparison with the current scenario. However, it is worth noting that the growth rates among hydroelectric, wind, and solar energies differ.

The annual energy estimates required for hydrogen production, based on the electric vehicle adoption projection conducted by EPE, followed the same methodological approach outlined in subsection 2.2. In this approach, the quantity of hydrogen, expressed in kg, was determined through the correlation between the growth of the hydrogen-powered vehicle fleet, the average distance traveled by the model vehicle, and its specific consumption. Subsequently, the energy required for hydrogen production was determined, while considering the total quantity of hydrogen demanded, the hydrogen higher heating value and the operational efficiency of the electrolyzer.

3. RESULTS AND DISCUSSION

In accordance with the Brazilian Ministry of Transportation, the current number of light vehicles running in Brazil exceeds 60 million, with an average annual distance traveled of 784.5 billion kilometers. This results in a hydrogen production of 6.6 billion kilograms per year if all vehicles were hydrogen-powered. This value is six times higher than the current hydrogen production in Brazil, which is 1 million tons (Agência Senado, 2023). The energy required to produce hydrogen to meet the demand required by a fleet composed entirely of hydrogen-vehicles in Brazil is around 351.42 TWh. However, considering the expected slow inclusion of these vehicles into the fleet, it is necessary to analyze this result in a more detailed manner. Thus, Figure 1 provides an overview of the relationship between the required energy for hydrogen production and the incremental addition of hydrogen vehicles as a fraction of the Brazilian vehicle fleet.

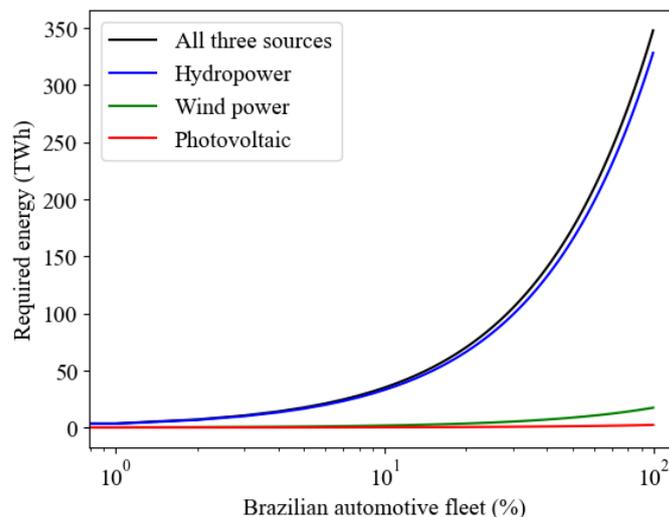


Figure 1. Energy required for hydrogen production as a function of the share of hydrogen vehicles in Brazil.

Observing the contribution of each renewable energy source, it can be noted that the PV curve shows little variation, despite the presence of 18,000 installed panels. Hydroelectric power plants would be the main contributors to green hydrogen production in Brazil, with approximately 69.9 TWh originating from ITAIPU (Itaipu Binacional, 2023), and the remaining amount coming from the 1,365 hydropower plants installed throughout the Brazilian territory. On the other hand, wind power has 930 operational wind turbines (ANEEL, 2023b).

In comparison to the electricity produced in Brazil, represented by its power grid, Figure 2 shows the relationship between the useful energy generated by renewable hydropower, wind, and photovoltaic sources and the energy required to add 100% of the vehicle fleet.

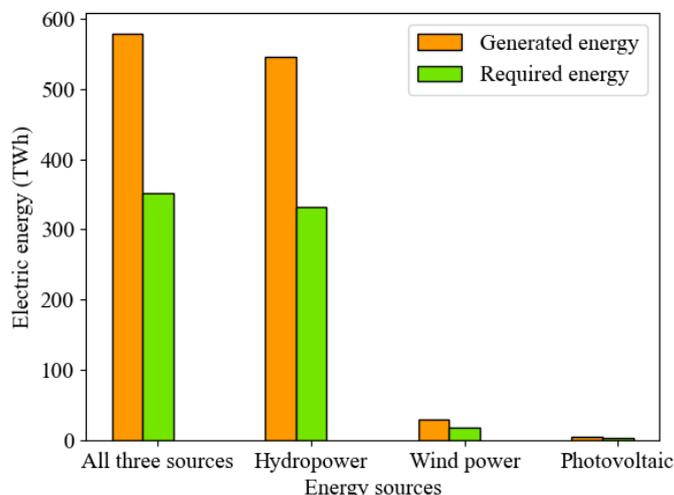


Figure 2. Comparison between generated energy and energy required for 100% of the Brazilian hydrogen vehicle fleet.

Therefore, in the scenario where all vehicles in the Brazilian vehicle fleet are converted to hydrogen-powered vehicles, 60.7% of the renewable share of the Brazilian power grid would need to be added to the current electricity production and directed towards the transportation sector, specifically for light vehicles. This becomes unfeasible because, although Brazil is self-sufficient in terms of electricity production, the available surplus margin of the power grid, which is exported, is not sufficient. In 2020, Brazil exported only 0.27 TWh of electricity (IEA, 2020), and the same amount was exported to Uruguay in February 2023 (Ministry of Mines and Energy, 2023). In other words, Brazil's electricity exports represent less than 0.5% of the production from the three main renewable energy sources. Faced with this limitation of surplus energy, it is necessary to evaluate whether the growth of Brazil's power grid is sufficient to accommodate the country's growth alongside the growth of hydrogen-powered vehicles, considering that the addition of these vehicles will be gradual.

Figure 3 presents the required growth of Brazil's power grid in relation to the increase in the hydrogen vehicle fleet over the next 10 years, based on the light vehicle fleet data from April 2023. Based on the data provided by EPE, Brazil has 168,884 electric and/or hybrid vehicles in 2023, and the exponential projection for 2032 would result in 1,597,198 cars of the same type. The difference between these two values encompasses 1,428,314 electric and hybrid vehicles acquired over a decade, representing an increase of approximately 2.4% of the current Brazilian vehicle fleet. In relation to this trend, the combined energy share from hydroelectric power plants, wind farms, and photovoltaic stations needs to grow by more than 1.4% in order for the Brazilian power grid to be able to supply the energy demanded by the increase in hydrogen-powered vehicles in 10 years.

Also, it is necessary to highlight that, in order to meet the hydrogen demand, the increase in Brazil's renewable energy generation over 10 years needs to be 1.4% higher than the expected electric growth rate for 2032. This is because energy consumption naturally increases annually, in direct relation to the country's gross domestic product (GDP) growth. According to the Ten-Year Energy Expansion Plan 2030 (EPE, 2021), the projected increase for hydropower plants from 2020 to 2030 is 93 TWh, a value that has already been achieved in 2023. Wind power, on the other hand, is expected to experience a growth of 100 TWh compared to 2023, and photovoltaic energy (both centralized and distributed) will contribute an additional 34 TWh. To achieve these targets, 204 MW, 4,488 MW, and 1,675 MW of capacity have already been contracted and will be added to the hydroelectric, wind, and PV plants, respectively. When combined with other renewable energy sources in Brazil, such as biomass, it is estimated that these sources will have an average annual growth of 2.8% in the Internal Energy Supply.

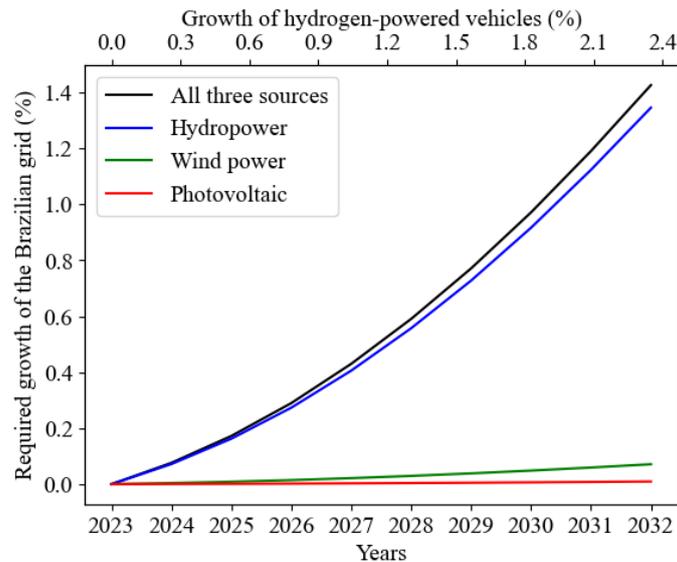


Figure 3. Required growth of Brazil's power grid + growth of hydrogen-powered vehicles.

Finally, projections regarding the contribution share of the three renewable energy sources by 2030 estimate that the share of the Brazilian grid influenced by hydroelectric power will decrease, while the shares of wind and solar energy will increase exponentially. In terms of the complete energy grid, it is expected that by 2030, hydroelectric power will represent only 49% of the matrix, wind energy will represent 13%, and solar energy will represent 4% (Hein, 2021).

4. CONCLUSION

In Brazil, hydropower, wind, and photovoltaic energies demonstrate a high potential for hydrogen production. However, large-scale hydrogen production to meet the demand of hydrogen-powered vehicles in the Brazilian vehicle fleet still faces significant challenges, with the renewable energy portion of the power grid dedicated to hydrogen production in the development and expansion phase.

If all light vehicles in Brazil were hydrogen-powered, approximately 6.6 billion kilograms of hydrogen would be required annually, which is six times greater than the current hydrogen production in the country. Additionally, it would be required 351.42 TWh of electricity production. Compared to the current production from hydroelectric, wind, and photovoltaic sources, the analysis shows that approximately 60.7% of the actual renewable portion of Brazil's energy grid would be needed solely dedicated to the production of hydrogen to fuel light vehicles.

Therefore, the gradual increase in the vehicle fleet and renewable hydrogen production was analyzed in accordance with the growth of Brazil's renewable power grid. With a projected increase of 1,428,314 hydrogen-powered cars over a 10-year period, the Brazilian renewable energy grid, excluding biomass, needs to increase by 1.4% between 2023 and 2032. However, this value needs to exceed the expected growth accompanying the country's development. Despite the substantial increase in the energy required, only 2.4% of the vehicle fleet would be added as hydrogen-powered vehicles. In line with the expected growth of energy in Brazil's power grid, the future scenario is favorable, as the growth of renewable energies in Brazil reaches 2.8% per year, which represents twice the necessary growth estimated to meet the hydrogen demand at the end of 10 years.

5. ACKNOWLEDGEMENTS

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