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Towards the Hydrogen Economy in Paraguay: Green hydrogen production potential and end-uses

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HIGHLIGHTS

- The estimated green H_2 production potential in Paraguay is 22.5×10^6 tons/year.
- The H_2 produced exceeds the demand of fuels in the selected sectors.
- In urban mobility, FCHEB buses have environmental advantages and economic disadvantages.
- An important reduction in GHG emissions could be achieved throughout green H_2 use.
- The development of the Hydrogen Economy in Paraguay fosters its energy transition.

ARTICLE INFO

Article history:
Received 30 January 2022
Received in revised form
1 May 2022
Accepted 23 May 2022
Available online xxx

Keywords:
Hydrogen economy
Green hydrogen production
Green hydrogen end-uses
Sustainable mobility

ABSTRACT

This study was conducted to estimate the potential for green H_2 in Paraguay. A total production potential of 22.5×10^6 tons/year was obtained with a main contribution (93.34%) from solar photovoltaic. The greatest potential for producing H_2 from solar and wind resources is in the Western region, and from hydro resources is in the Eastern region of the country. Two end-uses of green H_2 were assessed: (1) automotive transportation, replacing gasoline and diesel; and (2) residential energy, replacing firewood and LPG for cooking in households across the country. In 16 of the 17 departments, green H_2 is able to replace the overall consumption of gasoline and diesel, as well as firewood and LPG. Finally, energy service cost (mobility), environmental aspects and CO_2 emissions were considered for three urban mobility technologies for the Metropolitan Area of Asunción. Results show that the mobility cost of fuel cell hybrid electric buses is still very high in comparison to diesel buses and battery electric buses. However, when a longer driving range is required, fuel cell hybrid electric buses could become a viable alternative in the long term. From an environmental point of view, green H_2 used in fuel cell hybrid electric buses has the potential to save about 96% of CO_2 emissions in comparison to diesel buses. It is concluded that the estimated green H_2 production potential favors the incorporation of the Hydrogen Economy in Paraguay.

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https://doi.org/10.1016/j.ijhydene.2022.05.217

Please cite this article as: Posso F et al., Towards the Hydrogen Economy in Paraguay: Green hydrogen production potential and end-uses, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.05.217

Introduction

The Hydrogen Economy constitutes an innovative energy infrastructure that proposes the widespread use of H_2 from renewable resources, green H_2, to meet the energy needs of the main sectors of society [1]. It is currently undergoing accelerated development as it is considered an attractive option to advance the decarbonization of society, the energy transition, and promote economic recovery in a post-COVID-19 pandemic scenario [2,3].

The importance of the Hydrogen Economy has been discussed in several publications. In Ref. [4], green H_2's ability to create a virtuous cycle in renewable electricity generation by using surpluses for H_2 production is emphasized, with favorable effects on the plant capacity factor and the stability and flexibility of the electrical grid. Green H_2 is stored and converted into electricity to cover demand peaks, completing the cycle. In this way, green H_2 contributes to the sustainability of renewable generation. At the same time, the possibility of green H_2 to decarbonize the economy in two ways is analyzed: as a chemical input in industrial processes, such as oil refining and upgrading, and in the production of ammonia and nitrogenous fertilizers [5]. Both processes are large consumers of gray H_2. As an energy vector, the intervention of H_2 is extensive: as a fuel in thermal generation, the provision of heat in homes and offices, and the propulsion of vehicles with internal combustion engines; and as a source of electricity for use in all sectors of the economy via fuel cells.

This versatility of uses and applications of H_2 is one of the distinctive characteristics of the Hydrogen Economy as an infrastructure for the provision and use of clean and sustainable energy, which has a favorable impact in any field and purpose of intervention. As a result, in Ref. [6] is stated that the way to overcome health, environmental, and climate change challenges is to implement two fundamental paradigms: primary renewable energy sources and a green hydrogen society, taking advantage of the complementarity and synergy between both energy vectors.

All that has been mentioned previously explains the intention of many countries to have roadmaps or prospective studies on the gradual incorporation of the Hydrogen Economy into their energy mix [7]. In Latin America and the Caribbean, LAC, Chile [8] and, more recently, Colombia [9] and Paraguay [10], the country on which this study is focused, can be mentioned.

However, the net impact of green H_2 must be assessed based on its advantages and disadvantages, a topic that has been widely considered in the literature. This study reviews it from two dimensions. The first is related to the physical, chemical, and energetic properties of H_2, and the second is focused mainly on the status and performance of the technologies of the Hydrogen Economy value chain and the barriers to be overcome to achieve the massive penetration of H_2 in all sectors of a country's or region's economy. In this context, in Ref. [11], its distinctive properties with respect to other fuels are described. Among them are its high specific energy content (energy/mass) and high stoichiometric air/fuel ratio (kg), minimum ignition and self-ignition temperature, maximum combustion and diffusion speed, wide flammability range, abundance in nature, and high-performance indicator in its conversion to useful energy in fuel cells due to its lack of restrictions Carnot cycle restrictions. In contrast, several disadvantages are pointed out: its production and storage consume energy, which decreases the net amount of its useable theoretical energy content. Its handling requires rigorous safety mechanisms and protocols that take into account its diffusivity, flammability, and ignition and self-ignition temperatures. Storage technologies must also incorporate suitable materials and devices to minimize escapes and leaks, which leads to increased costs and operational complexity. In the same way, a study [12] pointed out that green H_2 is emerging as a promising fuel for the energy transition due to its high energy density, high conversion efficiency, storage potential, and environmental friendliness. However, factors that are slowing down its progress are also mentioned, such as the level of maturity of its technologies, social acceptance of its use, and the ability (through learning) to penetrate the industrial and mobility markets.

While in Ref. [13], a geopolitical analysis of the role of H_2 in the global energy transition, its advantages and disadvantages are listed. The advantages include: a) reducing foreign dependence on secondary energy, thereby contributing to countries' and regions' energy security; b) improving the flexibility and resilience of energy systems; in the first case, because it represents an ideal way of managing surpluses from renewable electricity generation; and in the second case, to contribute to access to energy services in rural, remote, or isolated regions from the electricity grid; c) mitigation of fossil fuel price volatility in the global energy market, highly sensitive to geopolitical conflicts resulting from the unequal geographical distribution of fossil energy sources, in contrast to the distributed nature of RESs, the energy base for green H_2 production. The following are mentioned as disadvantages: a) the costs and maturity of H_2 technologies; b) the low overall efficiency of the green H_2 value chain, for example, on the Power-to-Power or re-electrification route; c) the lack of public policies and regulatory framework for the incorporation of H_2 into the energy mix, as well as technical standards and certification of its use and management.

From a documentary review of studies on the Hydrogen Economy's development and the estimates of its potential in the Republic of Paraguay, it is obtained that most of these have focused on the use of the spilled turbinable energy (STE) from the Itaipu hydropower station to produce H_2 and its subsequent use as an energy vector or industrial input. Furthermore, studies on the use of other renewable primary energy sources to produce H_2 is scarce and focused on specific case studies. All of them are described chronologically below.

In 2011, a study was published that could be the pioneer study on the production and use of green H_2 in Paraguay [14], in which the use of the STE of the Itaipu hydropower station for large-scale H_2 production was explored. In Ref [15], the feasibility of fuel-cell-powered buses in the urban public transport system of several cities in the country is analyzed. The electricity required for H_2 production is obtained from the public distribution grid, resulting in beneficial economic outcomes. In [16] is described the development of a dynamic optimization technique for simulating electrolytic H_2 production and storage, as well as the usage of large volumes of STE at the Itaipu hydropower station. Additionally, in Ref. [17] is extended the developed optimization technique to H_2 and methane production and storage. Furthermore, a study [18] incorporated biomass as a feedstock to produce methanol by gasification and export to Brazil, and hydromethane by electrolysis and reforming for use as fuel in natural gas vehicles. The study is also based on STE use of Itaipu hydropower station.

Galeano studied the use of fuel cells for distributed generation using molten carbonate fuel cells [19]. The case study is located in the town of Bahía Negra in the department of Alto Paraguay. In Ref. [20], an innovative route for H_2 and N_2 production is proposed, with energy from the Itaipu hydropower station as the primary source of energy for both processes. Subsequently, both molecules react with each other to produce ammonia by the Haber-Bosch process. Meanwhile, in Ref. [21] is proposed the combination of solar photovoltaic energy and brackish groundwater for H_2 production for energy and industrial purposes at a site located in the western region of Paraguay. In Ref. [22], the potential for H_2 production from electricity in excess of the use of wind energy and hydropower in Brazil is valued, technically and economically, because both countries share the operation and generation of Itaipu hydropower station.

Finally, a study of green H_2 production in several South American countries [23] about the use of STE from hydropower stations in Argentina, Uruguay, and Paraguay is reported. The latter, the Itaipu and Yacyretá hydropower stations, are considered, and the energy and chemical use of green H_2 is analyzed, technically and economically, concluding that this production route is feasible to implement in the country due to the low cost of the electricity required for electrolytic H_2 production.

From all that has been exposed previously, it can be deduced that the route for green H_2 production from hydropower, of the STE type of the Itaipu hydropower station, has been extensively studied in Paraguay. However, the use of small hydropower stations scattered throughout the country, as well as other renewable primary energies for green electrolytic H_2 has been scarcely studied. This study aims to contribute to overcoming this knowledge gap by providing departmental distribution maps of green H_2 potential across the country for each of the primary renewable energy sources included in the study: wind, solar photovoltaic, and hydropower. Another contribution to knowledge is related to the use of H_2 as fuel in homes and the transport sector, in terms of departmental distribution maps.

Another aspect of this study has to do with the use of green H_2 as fuel in public transportation buses in the metropolitan area of Asunción and its comparison with traditional buses powered by diesel internal combustion engines and battery electric buses. In this case, from the documentary review on the use of green H_2 in sustainable mobility in Paraguay and other nearby countries, several studies are reported. In Ref. [15], fuel-cell-powered buses to traditional diesel-powered buses is compared, but does not include electric buses. Another study [24] presents a review of studies and data on lithium resources, batteries, and electric cars, along with an exploratory study of the feasibility of replacing car fleets for personal transportation using internal combustion engines (currently used in Paraguay and Bolivia) with equivalent electric vehicles. Moreover, In Ref. [25] key results of the analysis of different transport modes in Paraguay, Brazil, and Argentina is summarized. Hydro-methane is produced in Paraguay and can be used to fuel natural gas vehicles, thereby substituting gasoline and diesel, which are at the moment imported from foreign countries. Methanol, also produced in Paraguay, is delivered to Brazil, which is one of the countries with the highest demand in the region. Oxygen can be sold to Argentina for medical and industrial use. Carbon dioxide is delivered throughout Paraguay. In Ref. [25], the cost of the energy service (mobility, US$/km) for a fleet of 16 fuel cell hybrid electric buses was estimated considering a decentralized production of electrolytic H_2 using proton exchange membrane electrolyzers (PEM) and alkaline electrolyzers (AEL). This report does not compare the obtained cost of the energy service with that of diesel internal combustion engine buses and battery electric buses.

In this context, this study has three objectives: the first is to estimate the green H_2 production potential via electrolysis of water from RES in Paraguay; the second is to analyze its use in two identified opportunity niches, the residential and transportation sectors, replacing firewood and liquefied petroleum gas (LPG) in the first and diesel and gasoline in the second. In both cases, the results are expressed on maps for a better visualization of both the green H_2 potential as well as the potential to replace selected fuels for cooking and mobility. The third objective is to compare three urban bus technologies, diesel internal combustion engine bus (DICEB), battery electric bus (BEB) and fuel cell hybrid electric bus (FCHEB), for public transport in the Metropolitan Area of Asunción, with a special focus on their energy service cost (mobility, US$/km), as well as their Well-To-Wheels CO_2 emissions.

This study contributes to existing knowledge in Paraguay on the routes of green H_2 production and consumption, assisting in its gradual integration into the country's energy mix. As a result, it could serve as a reference study for the country's energy transition planning, prospecting for 2050 [26], and guidelines established in its national green H_2 roadmap [10]. The study's contribution to the study of green H_2 application in sustainable mobility is evident in the comparison of mass transportation systems in buses. Its findings, which take into consideration the country's comparative advantages in renewable generation costs, could serve as a foundation for more specific and detailed projects.

All these findings would provide elements for decision-making in the Hydrogen Economy's eventual incorporation into Paraguay's energy mix. Indeed, a report on the formulation of H_2 development strategies in Latin America [27] emphasizes the importance of knowledge gained from the creation of a development baseline, as well as the role of H_2 in energy transition planning. In addition, the importance of formulating a national H_2 strategy to achieve timely and sustainable transit from a niche of initial opportunity to a wide deployment in all sectors of the economy is established in another report with recommendations for the formulation of policies for the incorporation of H_2 into a country's energy mix [28]. In this construction, the definition of the baseline that identifies potential low-carbon production routes and demand sectors is essential. Therefore, the results of this study contribute to the identification of opportunities and the application of key technologies, clean production routes and demand sectors by making available departmental distribution maps of production potential and uses of H_2 in Paraguay that show the most attractive locations and development opportunity niches by reconciling the potential supply and demand of green H_2.

Overview of the energy mix of Paraguay

For the purpose of this study, several topics related to the energy mix of Paraguay are presented. Thus, the supply and the demand of primary and secondary energy and its environmental effects are described and analyzed. The reference information comes from the National Energy Balance 2020 [29] and the International Renewable Energy Agency (IRENA) report on the level of development of the RESs in the country and their role in the diversification of its energy mix and energy transition [30].

Total energy supply

According to its origin, Paraguay's energy supply has a national and a foreign component. The first represents the production of primary energy, with a contribution of 76% of the total energy supplied, while the second comprises the import of secondary energy, which represents 23%, Table 1. This first result constitutes the first distinctive characteristic of the country's energy mix: its high external dependence on secondary energy, which shows a structural weakness, even with possible implications for energy sovereignty.

Regarding the production of primary energy, its two main contributors are hydropower, which contributes 49% of total production and generates 99.5% of the country's electricity through energy conversion; and biomass, which accounts for 34% of the total. This is the second distinctive feature of the Paraguayan energy mix: the predominance of RES in the country's primary energy production.

Total energy demand

According to the type of source

In this case, consumption is distributed between biomass representing 42%; fossil fuels accounting for 39%, and electricity which accounts for 19% of demand from secondary sources, Table 2.

According to the demand sector

Historically, the transport sector has been the main consumer of secondary energy, especially fossil fuels, for mobility in all modalities, Fig. 1. Starting in 2016, the behavior of consumption shows a slight variation that is estimated to change in the 2020 report due to the strong negative impact of the COVID-19 pandemic in all areas.

From the combination of these items, energy source and demand sector, it is observed that biomass has a wide presence in the industrial and residential sectors, Fig. 2. It can also be observed that fossil fuels dominate in the transport sector with the gradual penetration of bioalcohols forming blended fuel, while electricity is present in all sectors.

Table 1 – Paraguay energy supply 2020 [29].

Item		Value (GJ)
Primary production		190.8
Importation	Primary	19.1
	Secondary	58.2
Inventory variation		1003.1
Untapped energy		2292.8
Total		**252,400.3**

Fossil fuels demand

In 2020, the consumption of fossil fuels, gasoline, and diesel, did not change its historical trend, of which 95% is in the transportation sector, where diesel represents approximately 2/3 of the total, Fig. 3.

RES in the energy mix of Paraguay

Paraguay is one of the few LAC countries with high participation of RES in the structure of energy supply and consumption, representing 77% of its total supply. Thus, hydropower represents 99.5% of the country's installed capacity, 8832 MW, while biomass, of the firewood type, has traditionally been used in the industrial and residential sectors as a source of heat for processes in the first sector and for cooking in the second. Recently, the consumption of residual biomass from sugarcane and corn crops has emerged as a new source to produce biofuels. On the other hand, the country has attractive potential in certain regions, thus indicating a significant annual average solar energy potential, between 1850 and 2,000 kWh/m^2-year in the north and northeast of the country, and between 1500 and 1800 kWh/m^2-year in the south and southeast of the country [30].

Regarding the wind potential, an intensity of attractive winds has been detected in the northwest of the country, especially in the west of the department of Boquerón, with average wind speeds of 6.5 m/s at 50 m above ground, representing 3500 to 4500 kWh/m^2-year. However, only small sites can be reported for localized purposes without any noticeable effect on power generation. This is the third distinctive aspect of Paraguay's energy mix, the null participation in the national energy supply of the so-called modern renewable energies, solar photovoltaic, solar thermal, and wind [30].

Table 2 – Energy consumption according to the source and type in Paraguay, 2020 [29].

Source	Type	Value (GJ)
Biomass	Firewood	40,697.4
	Charcoal	5158.8
	Others	724
	Total	46,580.2
Petroleum derivatives	LPG	2268.9
	Gasolines	15,404.8
	Diesel	36,732.7
	Others	4227.4
	Total	57,200.8
Hydro	Electricity	28,182.5
Total		**252,400.3**

Please cite this article as: Posso F et al., Towards the Hydrogen Economy in Paraguay: Green hydrogen production potential and end-uses, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.05.217

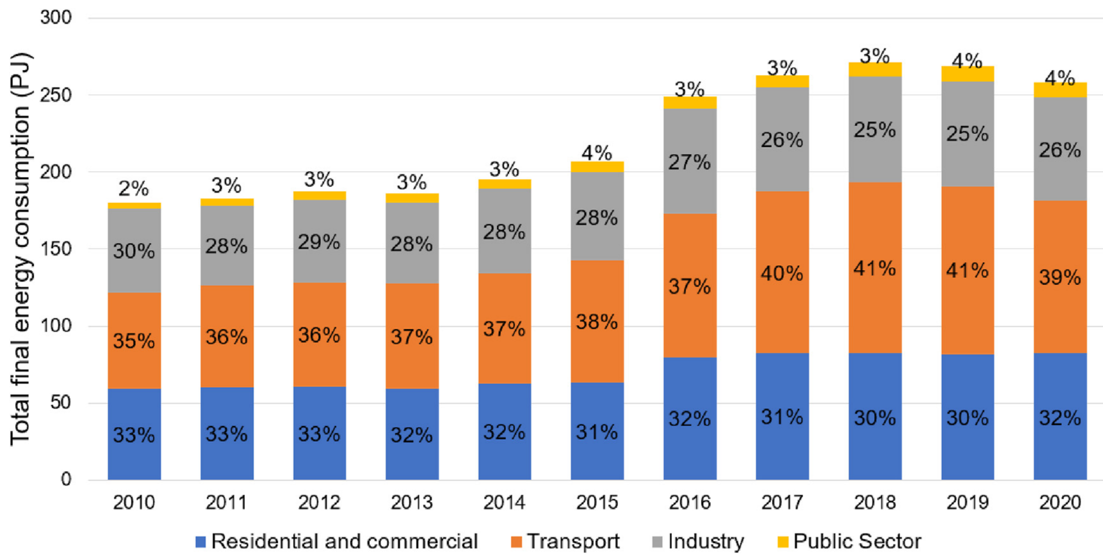

Fig. 1 – Behavior of energy demand in Paraguay according to the consumption sector, 2010 to 2020 [29,31–35].

Summary

Paraguay's energy mix presents several differentiating characteristics, including high penetration of RES in both the supply and consumption of energy. Foreign dependence on the supply of fossil fuels is destined mainly for mobility and minimum use of the country's renewable solar and wind resources. In this scenario, the diversification of the energy mix, the complementarity and future substitution of fossil fuels by other energy vectors, and the use of other RES different from hydropower and biomass, represent opportunities for the progressive incorporation of the Hydrogen Economy into the country's energy mix, as indicated in official prospective studies, such as the National Energy Policy of Paraguay 2016–2040 [36] and the Hydrogen Roadmap [10].

Methodology

This study was done in three successive steps associated with the proposed objectives that are described in their essential aspects:

First step: RES assessment (wind, solar photovoltaic, and hydro) in each department (an administrative division of the country) of Paraguay[1] and estimation of power and electricity available for green H_2 production. For this, renewable resource data was used both statistically and graphically, using updated data from Refs. [35,37–39].

Second step: Calculation of the obtainable amount of green H_2 produced via electrolysis of water from selected RES in each department of Paraguay. The results are expressed in tables and maps that allow the reader to easily visualize the results. It is very important to emphasize that maps illustrate the potential to produce H_2 from wind, solar, and hydro in Paraguay, normalized by department area (H_2 ton/km^2), to minimize differences in values based on the size of areas so that they can be compared regardless of the size of the departments.

Third step: Analysis of green H_2 potential end-uses, considering the replacement of gasoline, diesel, LPG, and firewood in each department of Paraguay. The scope of this replacement is estimated by considering the energy equivalence between them based on the LHV and the demand for selected energy carriers at the departmental level. End-uses were focused on two sectors already identified as potential niche opportunities: transportation and residential [10].

In the first sector, it was proposed to replace gasoline and diesel with green H_2. In the second sector, it is intended to replace firewood and LPG with green H_2 as a heat source for cooking. Firewood is an inefficient and polluting energy source for cooking, and LPG is imported entirely from Bolivia and Argentina. Charcoal consumption was not considered in this study due to the informality of the sector in Paraguay, without reliable data, and with commercial consumers and industrial companies unwilling to share consumption and price data. Finally, energy service cost (mobility) and CO_2 emissions were calculated for three urban mobility technologies for the Metropolitan Area of Asunción: DICEBs, BEBs, and FCHEBs. These calculations and the environmental aspects presented in this paper are pioneering in Paraguay, since there are currently no similar studies in the country.

RES assessment and estimation of available electricity for green H_2 production in each department of Paraguay

Wind resource assessment

The use of wind energy is based on the conversion of kinetic wind energy into electricity through wind turbines, whose technologies have improved their performance and efficiency that have led to a decrease in production costs [40]. To determine wind-generated electricity in Paraguay, a wind resource estimation was made for each 5 km × 5 km grid cell using wind speed data from Ref. [37]. For initial wind

[1] Paraguay consists of 17 departments and one capital district. It is also divided into two regions: The Western region or Chaco (Boquerón, Alto Paraguay, and Presidente Hayes), and the Eastern region (the other departments and the capital district) [13].

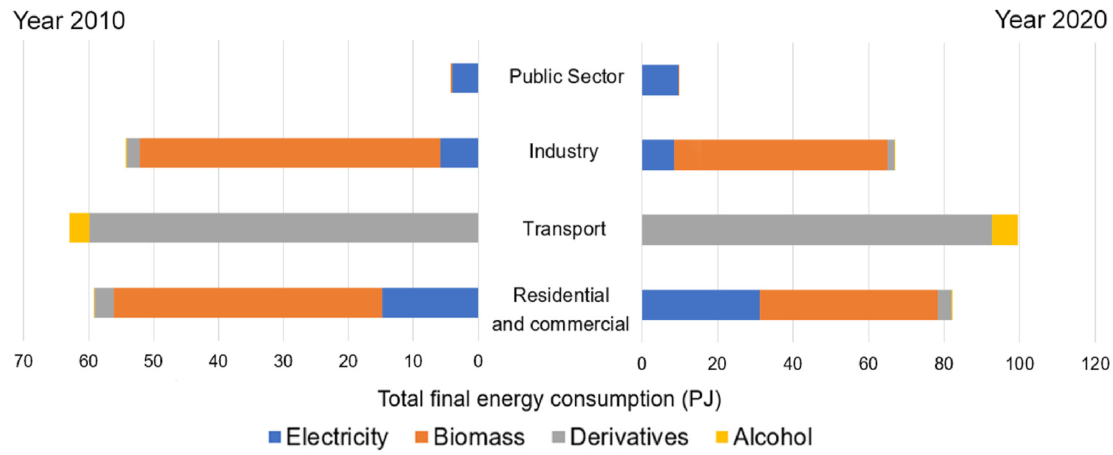

Fig. 2 – Energy demand variation in Paraguay according to the source and sector, 2010 and 2020 [29,31–35].

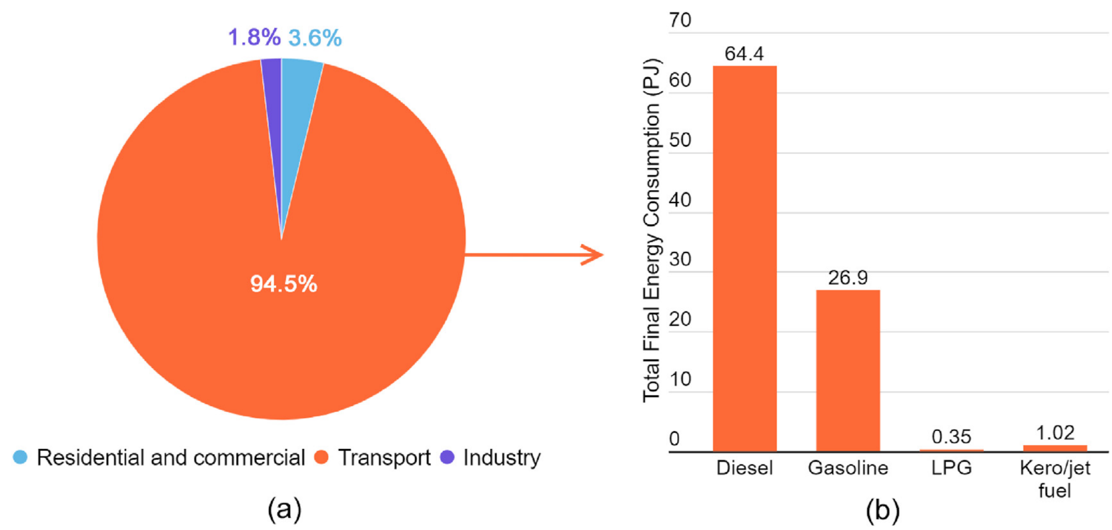

Fig. 3 – Consumption of petroleum derivatives (a) according to the sector, and (b) by source in the transportation sector, 2020 [29].

resource assessment, the average annual speed is considered to quantify the possible energy generation equipment to be used.

Mathematical model for commercial wind turbines. To calculate the energy obtained from a wind turbine, a mathematical model is used based on the wind turbine's performance as a function of the incident wind speed at the height of its axis [41]. In general, the mathematical model is given by the following expression:

$$P(v_{air}) = \begin{cases} 0, \text{ if } v_{air} \le v_{drive} \\ P_{nominal}, \text{ if } v_{air} \ge v_{nominal} \\ P_{nominal} \times m_{aero}, \text{ if } v_{air} \ge v_{drive} \end{cases} \quad (1)$$

$P(v_{air})$: power obtained as a function of air speed (kW).
v_{air}: air speed (m/s).
$P_{nominal}$: nominal air power (kW).
m_{aero}: power growth slope vs air speed (kW/(m/s)).
v_{drive}: turbine drive speed, typically above 3 m/s.
$v_{nominal}$: speed at which rated power is reached, typically 8–12 m/s.
$v_{disconnection}$: speed at which the wind turbine shuts down, normally 20–25 m/s.

The technical information of 30 commonly applied commercial wind turbines was considered to obtain the characteristic parameters presented in Table 3. Given the low levels of wind speed observed, the disconnection speed was not considered because in the available meteorological information, these values were not reached.

Selection of wind turbine size. Based on [37], the useable power per generator in each 5 km × 5 km grid cell and the capacity factor[2] were calculated. The capacity factor (CF) represents the energy output from a wind farm on an annual basis as a percentage of the farm's maximum output and is predominantly determined by two factors: 1) the quality of the wind resources where the wind farm is sited and 2) the turbine and balance-of-plant technology used [41]. Commonly, the CF in renewable energy systems with high resource variability is low. In the case of wind energy, an acceptable CF is about 0.18. It is considered very good above 0.24 [42], and there has been reported CF $\geq$ 0.30 [43].

Once the CF for the country's distribution has been calculated, Fig. 4 shows that a 2.5 MW wind turbine has the best relative performance, reaching 1561 grid cells suitable for wind energy production and even reaching 944 grid cells with a wind power CF $\geq$ 20%.

Wind turbines of 2.5 MW have better performance at low speeds, having an activation speed of 3 m/s, compared to other models whose activation speed is 4 or 5 m/s. This low activation speed explains the relative increase in the number of grid cells that have a CF $\geq$ 18%, even with values above 22%. In this study the following common general technical characteristics of 2.5 MW wind turbines were assumed:

Rotor diameter: 90–120 m
Number of blades: 3
Output voltage: 690.0 V
Network frequency: 50/60 Hz
Nacelle height: 60–70 m

Determination of the number of wind turbines per grid cell. In a wind farm, wind turbines must be installed to avoid the propagation of turbulence and changes in wind direction, although some different arrangements can take advantage of the land conditions. A uniform distribution of wind turbines organized in a rectangular arrangement was considered to minimize the effects of turbulence in the air stream, Fig. 5, so the effect of the power produced is affected only by 10% of the useable energy [45,46].

With this distribution and considering the 5 km × 5 km grid cells, 50 wind turbines can be installed in 25 km^2 without considering urban limitations. This totals around 78,000 wind turbines for the entire country based on a CF of 18% and 15,200 wind turbines considering a CF upper to 22%.

Calculation of power for every grid cell. For selected grid cells whose CF is greater than 22%, the following equation is applied:

$$E_{grid\ cell} = P(\upsilon_{air}) \times N \times \eta_{arrange} \times \Delta t \quad (2)$$

where:

$E_{grid\ cell}$: total energy produced by the grid cell in a given period (MWh).

$P(\upsilon_{air})$: power obtained by each wind turbine as a function of the air speed.

[2] CF is defined as the wind turbine's actual energy output divided by the rated maximum turbine output for the year. When the wind turbine's CF at a given average annual wind speed is known, it allows a reliable calculation of the expected energy output per year [44].

Table 3 – Characteristics parameters of the mathematical models for wind turbines.

$P_{nominal}$ (kW)	m_{aero} (kW/(m/s))	υ_{drive} (m/s)	$\upsilon_{nominal}$ (m/s)
200	24.6	4	12
500	54.4	4	13
1500	190.7	4	11
2500	337.1	4	11
3500	455.7	4	11
4500	544.3	4	11
8000	877.8	4	13

υ_{air}: air speed (m/s)

N: number of wind turbines in the grid cell, 50 units.

$\eta_{arrange}$: for established dimensions, arrangement efficiency corresponds to 90%.

Δt: period considered for energy production. In this study it was assumed by month.

After applying eq. (2) in the 302 selected grid cells, Fig. 6 shows the monthly energy production.

Solar resource assessment

In this case, PV solar energy is considered, the base information to estimate H_2 green production potential is presented in Ref. [37]. Electricity could be obtained depending on a set of parameters. The first one is the percentage of the available area in each department, F_{AP}. Restrictions for installation and operation of PV modules deal with protected geographic areas, water bodies, and especially urban centers and scattered populations.

Therefore, population density is important for setting the value of the F_{AP} indicator. Thus, F_{AP} takes a value of 3% for USA [47]; while in Argentina it has been chosen at 4.5% [48], and for Ecuador, F_{AP} takes a value of 2% [40]. Considering the relation between the values of the F_{AP} indicator and the population density of the coucqntries mentioned, a mathematical expression, eq. (3), is constructed using a nonlinear regression method to calculate this factor for each department, Table 4. In eq. (3), P_D is the population density (people/km^2):

$$F_{AP} = 0.2257 \times P_D^{(-0.567)} \quad R^2 = 0.9992 \quad (3)$$

It can be observed that the most populated departments of Paraguay have the lowest F_{AP} indicator, evidencing an expected inverse relationship.

The expression for calculating the useable electricity from solar PV energy by department in Paraguay is:

$$E_{FV}(kWh/year) = I_{PA} \times \eta_{fv} \times A_d \times F_{AP} \times D_F \times f_d \times CF \times f_{lat} \times f_{shade} \times f_{serv} \times (365) \times (10) \quad (4)$$

Solar panels have improved substantially their efficiency and power output over the last few decades [49]. In this study, for PV conversion, η_{fv}, an average efficiency of 20%, of commercial PV modules, was assumed.

The average CF for new utility-scale solar PV increased by year of commissioning from 13.8% in 2010 to 16.1% in 2020 [50]. According to Ref. [51], the average annual CF for solar PV technology is 21%. In this study, a value of 16.1% for CF was assumed. Also, I_{PA} is the average total annual insolation by

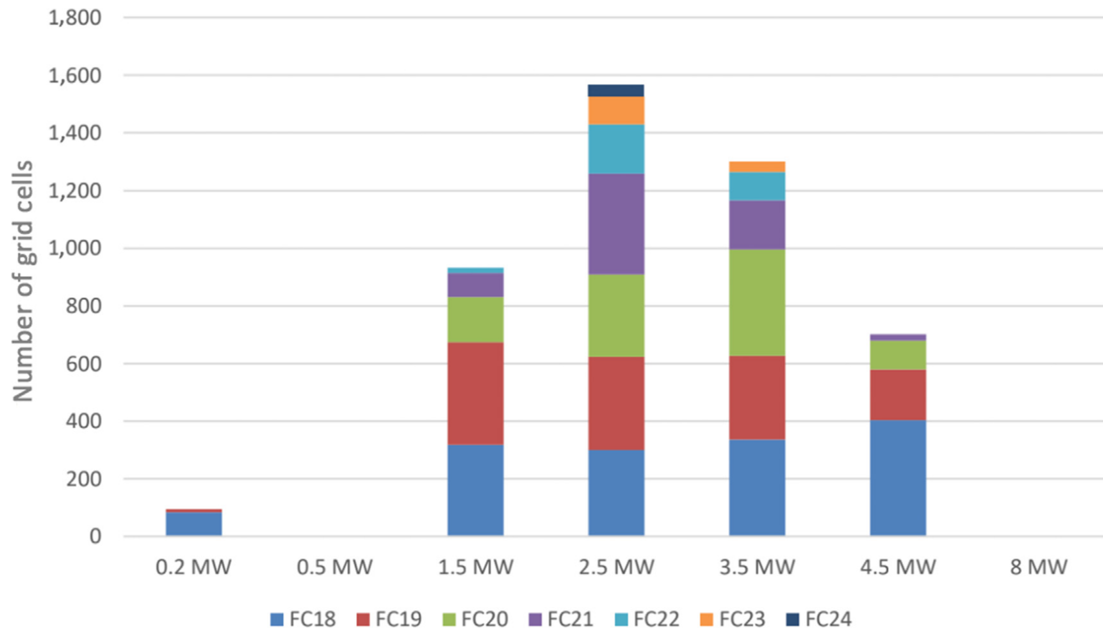

Fig. 4 — Grid cells distribution with CF suitable for commercial wind turbine capacities.

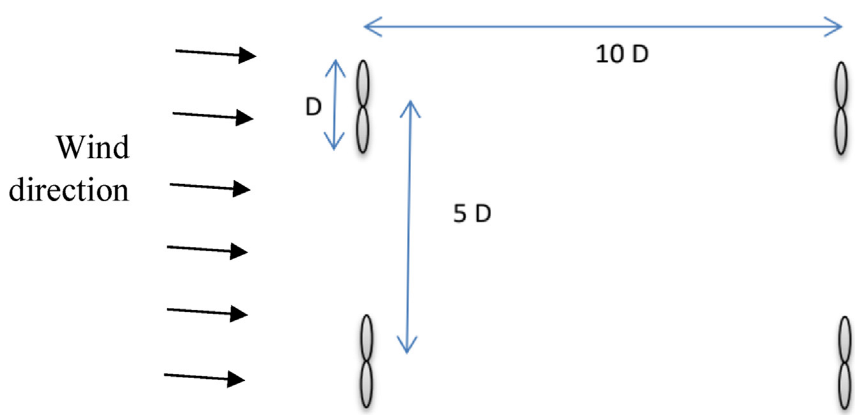

Fig. 5 — Rectangular distribution of wind turbines.

department, obtained by filtering the global insolation data of Paraguay [37], while the numerical value "10" is a conversion factor between units of different variables.

Under practical operating conditions, several power losses occur due to many causes, and it is useful to define a factor that relates the energy available from the PV array to the theoretical energy provided by the same array at STC.[3] This factor is called Derate Factor, D_F, and is generally found at about 0.7–0.8 [52]. D_F is assumed to be equal to 0.8 and the availability factor f_d to be equal to 0.95 [52].

The average latitude of Paraguay is −21.46°, so the global insolation on the photovoltaic panel varies its incidence throughout the year, the f_{lat} is considered as this geometric projection given by the cosine (−21.46°). Also, It is important to consider the array of photovoltaic panels over the area, there are spatial restrictions such as panel spacing for maintenance, installation, and most importantly, avoiding auto-shading. For PV arrays with a 20° tilt (close to the recommended tilt for Paraguay), studies consider a factor for PV shading ($f_{shading}$) of 80% and also suggest an area factor (f_{serv}) of 44% for giving staff access to photovoltaic arrays for servicing [53].

Hydro resource assessment

The information from Refs. [38,39,54] was used to assess the hydro resource; it shows the sites identified with hydropower potential equal to or greater than 5 MW. The estimation of hydro H_2 production potential in Paraguay was done by two methods.

The first method, as proposed by Refs. [40,55], is to assume that small hydro potential (less than 50 MW) that is economically available is intended for H_2 production. The procedure is to estimate the small hydro potential and then calculate the corresponding electricity depending on the generation availability and the CF. Small hydropower stations are mostly used to meet local electricity demands and provide peak power for grid-connected systems. The basic components of the

[3] Standard Test Conditions (STC), which are a radiation of 1 kW/m^2, a cell temperature of 25 °C, and no wind.

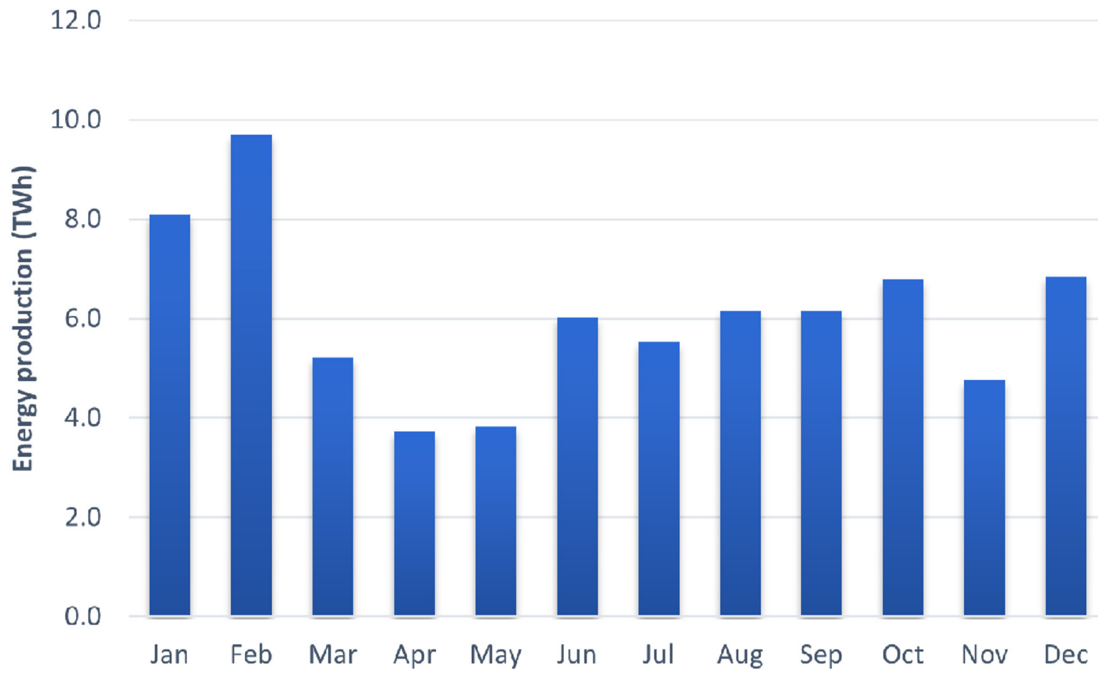

Fig. 6 — Monthly distribution of energy production by wind turbines (CF ≥ 22%).

Table 4 — F_{AP} indicator assumed for each department of Paraguay.

Department	Population density (people/km^2)	F_{AP} indicator
Distrito Capital	4454	0.2%
Concepción	14	5.0%
San Pedro	22	3.9%
Cordillera	64	2.1%
Guairá	60	2.2%
Caaguazú	50	2.5%
Caazapá	20	4.1%
Itapúa	38	2.9%
Misiones	14	5.1%
Paraguarí	30	3.3%
Alto Paraná	56	2.3%
Central	910	0.5%
Ñeembucú	7	7.2%
Amambay	13	5.2%
Canindeyú	16	4.6%
Presidente Hayes	2	16.2%
Boquerón	1	26.7%
Alto Paraguay	<1	52.5%
Paraguay	18	4.4%

hydropower-electrolyzer system under consideration are small hydropower station + electrolyzer system.

The second way to assess the available hydropower potential for H_2 production was based on using annual STE from Acaray, Itaipu, and Yacyretá dams between 2000 and 2019 [35]. STE refers to the power that could be generated from turbinable water that would otherwise be discarded for a variety of reasons. The potential to produce H_2 from STE is presented in ton H_2/year because hydro resources are centralized energy sources, unlike wind and solar resources, which are distributed energy sources. For both methods, the electrolyzer system is a "turn-key" installation consisting of electrolyzer cells, a water treatment unit, and either a compressor to compress generated H_2 if necessary or without a compressor delivering H_2 at process pressure.

Calculation of green H_2 production potential via electrolysis of water

The electrolysis process involves the use of renewable electricity to split water into H_2 and O_2 in the electrolyzer system. Electrolysis systems consist of a stack with electrodes and membranes, the balance of plant equipment that includes water tanks, gas separation units, dryers, recirculation pumps, power supply, and auxiliary equipment required for operation [56]. The electrolyzer's energy requirements in terms of efficiency relative to the HHV of H_2 vary depending on the type. The efficiency of the PEM electrolyzer in this study is summed up to 73.3%, which is the average of the values reported in other studies in the literature, Table 5.

Then:

$$P_{H_2} = \frac{E_D}{\eta_e} \tag{5}$$

where E_D is the electricity available for H_2 production (kWh/year) and may correspond to a value: for Itaipu, Yacyretá, and Acaray dams, in the case of hydropower type STE; for a department, in the case of solar PV, wind, and small hydro.

Analysis of green H_2 potential end-uses

The green H_2 potential end-uses in Paraguay are focused on two sectors: transportation and residential. In the first sector, the replacement of gasoline and diesel by green H_2 was proposed. In the second sector, it is intended to replace firewood and LPG with green H_2 as a source of heat for cooking. The

Table 5 – Electrolysis efficiency values reported in literature.

Reference	Efficiency, ηe (% of HHV)	Year	Comment
[27]	67–84	2019	Green H_2 production techno-economic analysis.
[28]	75	2020	Average of five commercial electrolysers.
[57]	60–84	2021	Technical report about electrolysers costs.

calculation method is similar to that used by Refs. [40,55,58,59]. The replacement is based on the energy equivalence in terms of the LHV of each fuel, Table 6, and the demand for these fuels by department, Table 7.

Thus:

$$1 \text{ kg } H_2 = 3 \text{ kg Gasoline} = 2.92 \text{ kg Diesel} \tag{6}$$

$$1 \text{ kg } H_2 = 2.38 \text{ kg LPG} = 7.95 \text{ kg Firewood} \tag{7}$$

Gasoline and diesel annual consumption in each department of Paraguay

In this section it was estimated the amount of gasoline and diesel consumption that could potentially be displaced by green H_2 in each department of Paraguay. Table 7 shows gasoline and diesel annual consumption by department for 2018 [61].

Firewood and LPG annual consumption in households for cooking in Paraguay

To replace firewood and LPG with green H_2 as a heat source for cooking in the residential sector, their consumption in each department was calculated. Then, eq. (7) was used to determine the green H_2 amount required to substitute them.

Several studies show a wide range in the per capita consumption of firewood in Paraguay. In Ref. [62], consumption at 2.86×10^6 tons in 2004 is reported, and in [63] is estimated this consumption at 2.58×10^6 tons in 2005. According to Ref. [64], this consumption varies between 0.6 and 8.0 tons/inhabitant/year for different sites in Paraguay's Eastern Region, with 65% destined for self-consumption. Based on [50], firewood consumption in Paraguayan households is approximately 1.8–2.7 ton/inhabitant/year, considering 4 members per household. Firewood consumption in Paraguayan households was calculated using official statistical data [65].

The LPG consumption in Paraguayan households in 2020 was 8.7×10^4 tons [66]. This fuel is totally imported, 80% from Bolivia and 20% from Argentina. The parameters considered to estimate the consumption of both fuels and the value of this consumption are shown in Tables 8 and 9, respectively.

As can be seen in Table 9, the highest demand corresponds to the departments of San Pedro, Caaguazú, and Itapúa. According to Ref. [34], more than 3.0×10^4 households did not use firewood for cooking in 2020 compared to 2019.

Table 6 – LHV and density of H_2, gasoline, diesel, firewood, and LPG [33,34,60].

Fuel	LHV (MJ/kg)	Density (kg/m^3)
H_2	120	0.09
Gasoline	39.9	814
Diesel	40.9	884
Firewood (20% moisture)	15.1	769
LPG	50.4	550

Results and discussion

In this section the results for green hydrogen production and end-uses are presented according to the RES used.

Potential for H_2 production from wind energy

Table 10 shows the number of wind turbines that could be used according to every capacity factor (CF) considered, and the overall hydrogen production for each scenario. Also are presented the rates of energy production and hydrogen production per wind turbine to appreciate the effectiveness of the system.

In terms of overall production, higher CF reduces turbine energy and hydrogen production because fewer turbines meet the wind velocity criteria, whereas lower CF increases turbine energy and hydrogen production since better wind resources are considered. Table 10 may also be used as a path for implementing wind energy because it is relevant to invest initially in places with higher CF and subsequently in places with less CF.

Table 11 shows the monthly distribution of electricity generation from wind energy in Paraguay and the corresponding electrolytic H_2 production potential. The wind resource in Paraguay is relatively low, since the average wind speed is less than 7 m/s, which makes the wind generation mechanisms exhibit a relatively low CF. However, it has been found that the use of 2.5 MW wind turbines gives a maximum number of zones that can present a CF $\geq$ 0.22.

Fig. 7 illustrates the potential to produce green H_2 from wind in Paraguay, normalized by area, for extreme production conditions.

It is shown that Boquerón is the leading department for wind H_2 production in Paraguay, particularly in February. Throughout the year, the month of April has the lowest wind resource availability. This behavior is due to the fact that the wind resource is influenced by large-scale physical factors as well as regional and local ones, such as terrain roughness or topography of a given area.

Potential for H_2 production from small hydro potential

Considering the first method of H_2 production from hydropower potential, according to Ref. [68] is valid to assume the economically available unexploded hydropower potential is 550 MW, and approximately 37% (202 MW) corresponds to small hydropower types. The corresponding electricity is

[4] n.d.a. = no data available.

Please cite this article as: Posso F et al., Towards the Hydrogen Economy in Paraguay: Green hydrogen production potential and end-uses, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.05.217

Table 7 – Gasoline and diesel annual consumption in Paraguay for 2018 (10^3 m^3/year) [61].

Department	Gasoline consumption	Diesel consumption
Distrito Capital	49.5	57.6
Concepción	12.3	16.6
San Pedro	17.6	24.9
Cordillera	13.3	16.2
Guairá	8.8	9.2
Caaguazú	22.8	39.8
Caazapá	4.8	4.8
Itapúa	26.7	44.9
Misiones	7.2	6.0
Paraguarí	8.5	8.1
Alto Paraná	61.9	91.2
Central	143.6	179.9
Ñeembucú	2.9	3.2
Amambay	25.4	20.5
Canindeyú	19.9	35.5
Presidente Hayes	5.6	20.7
Boquerón	4.5	27.5
Alto Paraguay	1.2	6.8
Paraguay	436.4	613.7

Table 8 – Values of the parameters used to estimate firewood and LPG consumption in households in Paraguay.

Parameter	Value	Unit	Ref.
Household	4	Members	[64–67]
Average firewood consumption	12.5	ton/household/year	[33]
Average LPG consumption	0.18	ton/household/year	[65]

calculated assuming its availability throughout the year and a plant factor, F_p, of 75% [39]. In this context, the hydro-H_2 production potential is shown in Table 12.

If this small hydro potential were used exclusively to produce electrolytic H_2, then the annual production potential would be 24.9×10^3 tons. Fig. 8 shows the annual H_2 production map.

According to Fig. 8, the Department of Alto Paraná presents the largest small hydro potential in the country and 50% of the annual H_2 production from this resource.

Potential for H_2 production from STE

The Itaipu and Yacyretá hydropower stations represent the largest installed generation capacity in the country and are integrated with the electricity systems of Brazil and Argentina. Acaray hydropower station is the third largest, followed by small thermal stations using diesel, bagasse, and biogas [30].

The production of green H_2 by taking advantage of the STE in hydroelectric plants with a reservoir is shown in Table 13. The STE exhibits year-to-year variability (Fig. 9), which is mainly due to hydrological conditions and has gotten worse as a consequence of climate change (droughts, precipitation amount and timing, and so on), as seen by its annual erratic behavior. Higher values of STE correspond to higher values of green H_2, following a direct proportionality relationship established by eq. (5). In 2016, a production peak of 286.5×10^3 tons of green H_2 was achieved (Table 13) indicating an excellent way to store this variable energy, which would otherwise be lost.

Table 9 – Annual average consumption of firewood and LPG by department in Paraguay, 2017 to 2019 (10^3 ton/year) [66].

Department	LPG	Firewood
Distrito Capital	17.1	137.9
Concepción	4.3	330.1
San Pedro	4.6	770.9
Cordillera	6.1	351.7
Guairá	3.6	340.0
Caaguazú	9.0	702.2
Caazapá	2.6	379.5
Itapúa	14.1	703.8
Misiones	3.3	139.3
Paraguarí	3.8	523.3
Alto Paraná	28.9	348.6
Central	64.0	266.5
Ñeembucú	2.8	110.5
Amambay	6.5	37.2
Canindeyú	5.9	267.5
Presidente Hayes	2.7	78.9
Boquerón	n.d.a.[4]	n.d.a.
Alto Paraguay	n.d.a.	n.d.a.
Paraguay	179.6	5216.6

Potential for H_2 production from solar energy

Based on [37], the variation interval of the annual average irradiation by department is estimated and the annual production of H_2 is calculated using eqs. (3) and (4). Its normalized values by department (or production density) are shown in Fig. 10.

Less populated departments in the country's western region (Boquerón, Alto Paraguay, and Presidente Hayes) combined with very good solar resources define the high H_2 potential from solar resources in this region and clearly show a high potential for producing H_2 from solar resources in Paraguay.

Analysis of green H_2 potential end-uses

Total green H_2 production

The consolidation of the contribution of each one of the RES included in the estimation gives a total green H_2 production potential of 22.5×10^6 tons/year, Fig. 11 shows the contribution of every selected RES, evidencing the predominance of solar PV energy.

The estimated total green H_2 annual production, 2695 PJ, covers entirely the secondary energy requirements of the country, 147.2 TJ for 2020, and the remainder could be used as a chemical feedstock in industrial processes such as ammonia and methanol production.

Table 10 – Annual energy and H_2 production by wind turbines and their relative performance.

CF	$N_{turbine}$	E_{annual} (PWh/year)	Performance (GWh/wind-turbine/year)	H_2 (x 10^6 ton)	H_2 production performance (ton/wind-turbine/year)
18	78,000	5.3	67.77	114.3	1465
20	48,200	3.4	71.42	74.4	1544
22	15,200	1.2	75.87	24.9	1641
24	1950	0.2	80.46	3.4	1740

Table 11 – Monthly distribution of wind electricity generation in Paraguay CF ≥ 0.22 and the corresponding green H_2 production potential.

Month	Power (GW)	Energy (TWh)	H_2 (x 10^3 ton)	Month	Power (GW)	Energy (TWh)	H_2 (x 10^3 ton)
January	12.5	8.1	151.9	July	8.5	5.5	103.2
February	14.9	9.7	181.9	August	9.5	6.2	116.3
March	8.1	5.2	97.5	September	9.5	6.2	116.3
April	5.7	3.7	69.4	October	10.5	6.8	127.6
May	5.9	3.8	71.3	November	7.4	4.8	90.1
June	9.3	6.0	112.5	December	10.6	6.8	127.5
TOTAL						**72.8**	**1365.8**

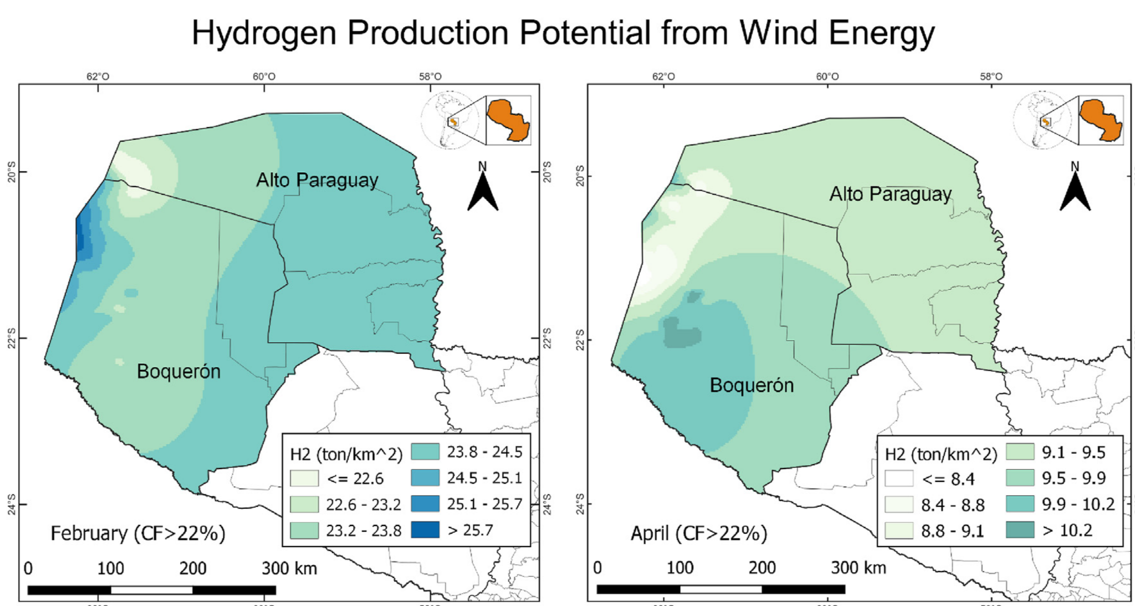

Fig. 7 – Normalized wind H_2 production map (best and worst scenario) in Paraguay.

Table 12 – Annual H_2 production from small hydro potential.

Department	Area (km^2)	Power (MW)	Energy (GWh)	H_2 production potential (ton)	(ton/km^2)
Amambay	12,933	7.6	50.2	942.0	0.07
Concepción	18,051	15.9	104.4	1958.7	0.11
San Pedro	20,002	22.4	147.2	2761.7	0.14
Canindeyú	14,667	23.3	153.1	2872.4	0.20
Alto Paraná	14,895	101.0	663.6	12,450.3	0.84
Itapúa	16,525	31.8	208.9	3919.3	0.24
PARAGUAY	**406,752**	**202.0**	**1327.4**	**24,904.3**	**0.06**

A summary of the potential reported in the literature and obtained for Paraguay is shown in Table 14. Although it is not possible to make a fair comparison between them because they correspond to different situations and conditions, it is useful to understand the order of magnitude of green H_2 production potential in Paraguay compared to other countries in America.

Green H_2 potential relative to gasoline and diesel consumption

Fig. 12 shows green H_2 production potential relative to gasoline and diesel consumption by department, observing that in 16 departments there is a percentage of substitution greater than 100% of the consumption of both fuels.

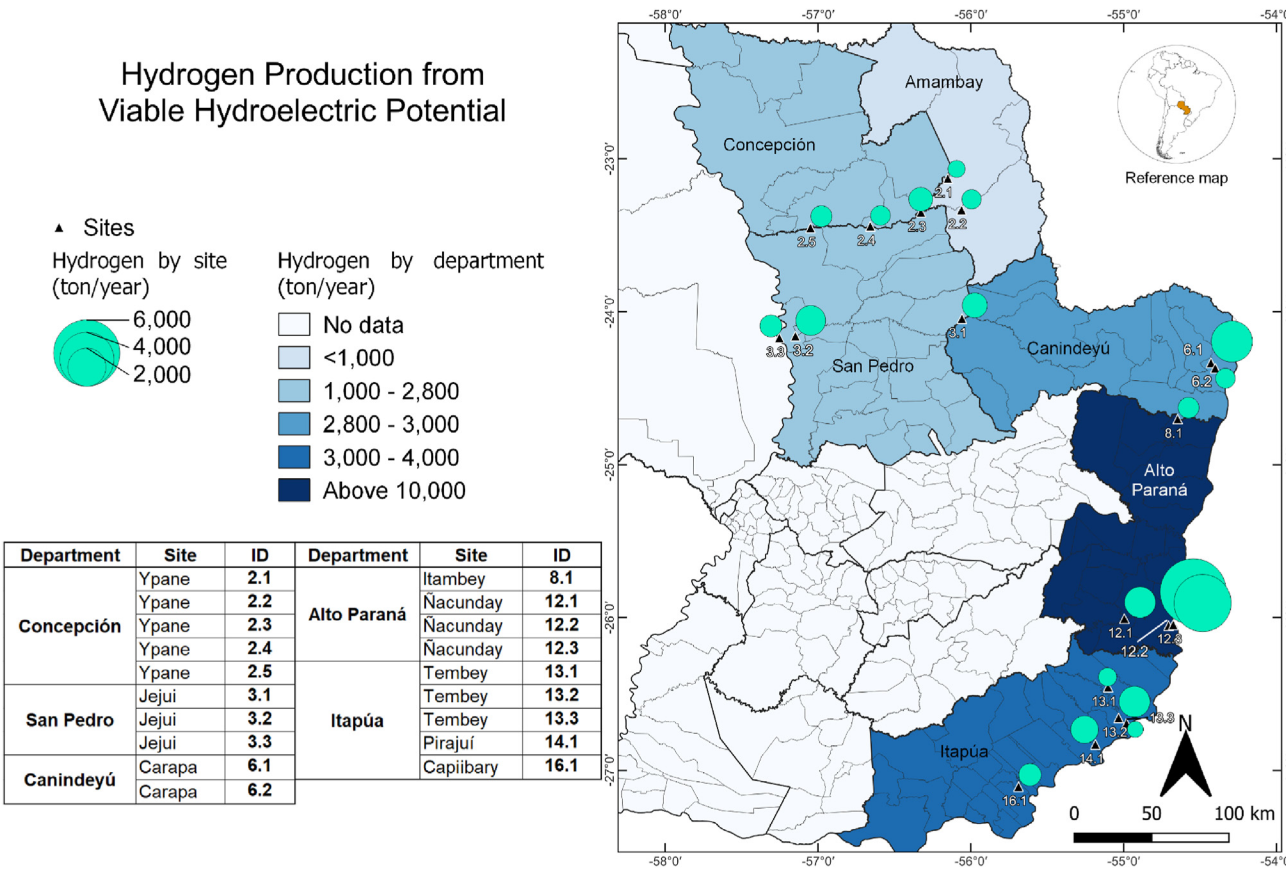

Fig. 8 – Annual H_2 production map from small hydro potential in Paraguay.

The departments of the Western region stand out because of their relatively low gasoline and diesel consumption and their high green H_2 production potential from solar and wind resources. However, the Capital District and the Central Department, the latter being the most populated department in Paraguay, cannot produce enough green H_2 to completely displace their high gasoline and diesel consumption. Thus, in the Capital District and in the Central Department, green H_2 could displace 0.2% and 3% of their gasoline and diesel consumption, respectively. However, they could rely on H_2 from surrounding departments.

Table 13 – Green H_2 production potential from STE of Itaipu, Yacyretá and Acaray dams.

Year	H_2 production (x 10^3 ton)	Year	H_2 production (x 10^3 ton)
2000	32.3	2010	179.1
2001	32.3	2011	152.9
2002	162.7	2012	67.9
2003	133.8	2013	123.8
2004	68.6	2014	95.9
2005	67.6	2015	209.7
2006	47.7	2016	286.5
2007	75.5	2017	101.1
2008	43.6	2018	92.2
2009	115.5	2019	38.6

Green H_2 potential relative to firewood and LPG consumption

Fig. 13 shows the production potential of green H_2 relative to firewood and LPG consumption by department in Paraguay, showing that it is possible to comprehensively satisfy the consumption of these fuels in all departments with local green H_2 production. It shows that the Capital District and Central Department cannot produce enough H_2 from selected renewable resources to completely displace their high firewood and LPG consumption. Green H_2 potential from selected RES could displace approximately 0.3% and 0.8% of firewood and LPG consumption in the Capital District, respectively, and 8.3% and 10.3% in the Central Department. However, in most cases, they could rely on H_2 from surrounding departments.

In contrast, the Department of Presidente Hayes in the Western region, because of its relatively low firewood and LPG consumption and high amounts of renewable solar and wind resources, has the potential to displace more than 290 times and 2550 times its current firewood and LPG demand, respectively.

Green H_2 as an alternative fuel in transport sector in Paraguay

The objective of this section is to analyze the possible future relevance of green H_2 in the transport sector, with a specific focus on the urban public transportation of the Metropolitan Area of Asunción. Three major configurations of buses were

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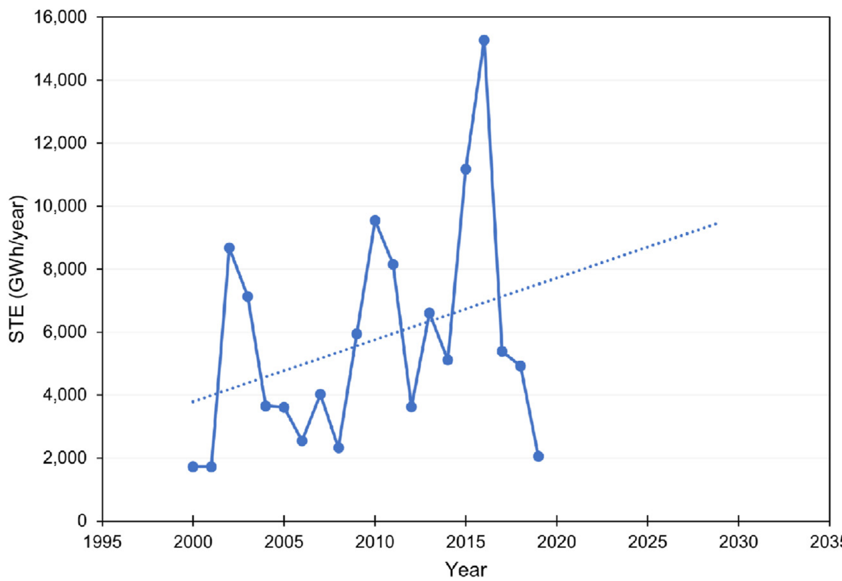
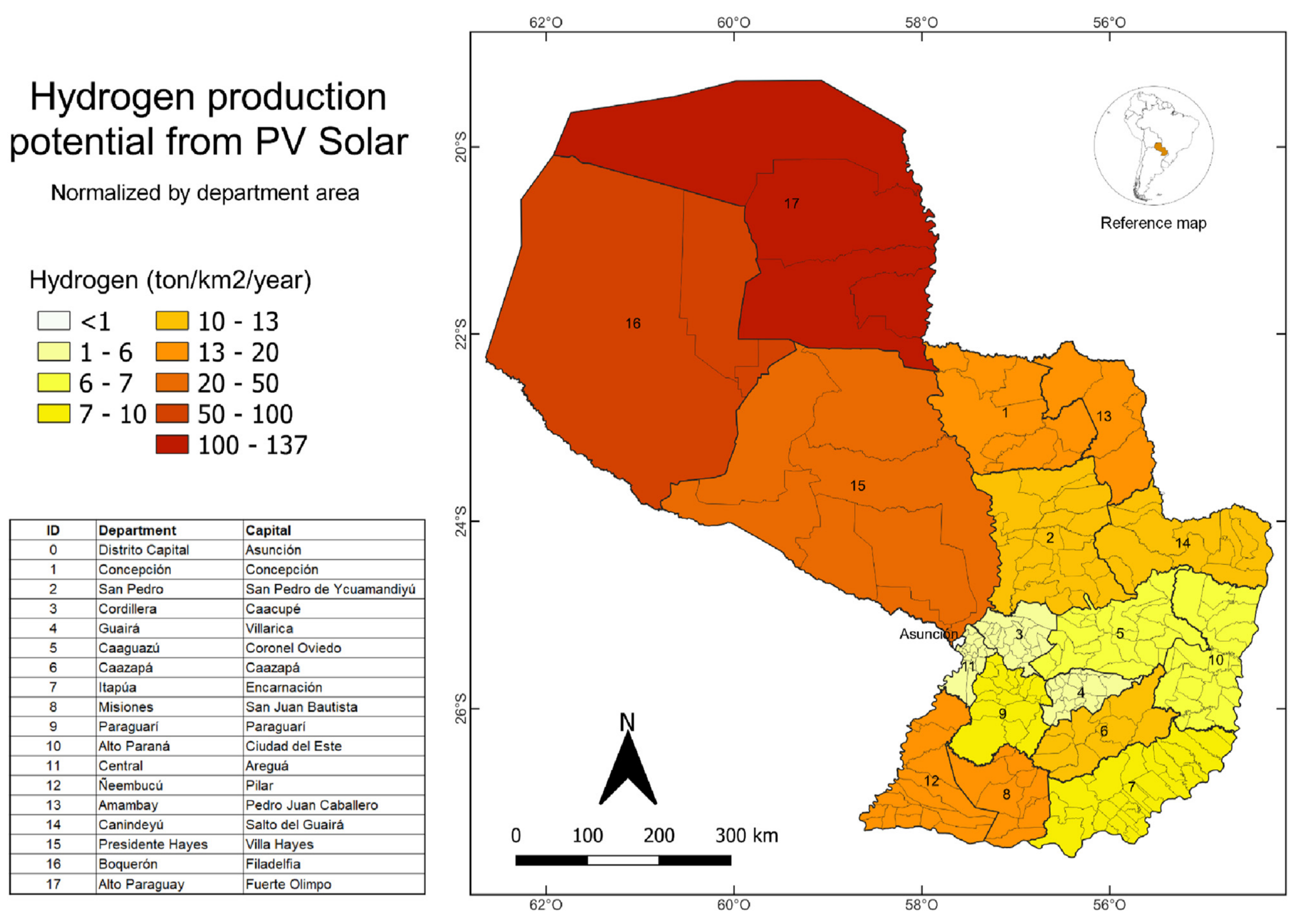


Fig. 9 — Historical and trend of STE (GWh/year). Source data [35].



ID	Department	Capital
0	Distrito Capital	Asunción
1	Concepción	Concepción
2	San Pedro	San Pedro de Ycuamandiyú
3	Cordillera	Caacupé
4	Guairá	Villarica
5	Caaguazú	Coronel Oviedo
6	Caazapá	Caazapá
7	Itapúa	Encarnación
8	Misiones	San Juan Bautista
9	Paraguarí	Paraguarí
10	Alto Paraná	Ciudad del Este
11	Central	Areguá
12	Ñeembucú	Pilar
13	Amambay	Pedro Juan Caballero
14	Canindeyú	Salto del Guairá
15	Presidente Hayes	Villa Hayes
16	Boquerón	Filadelfia
17	Alto Paraguay	Fuerte Olimpo

Fig. 10 — H_2 production potential normalized map from solar energy, by department in Paraguay.

considered, DICEB, BEB, FCHEB. Currently, the most used fuel cell bus configuration is a hybrid design with a battery. The batteries themselves provide the main driving force for the bus [73]. In this section, the major focus is on hybrid fuel cell buses, which are the most widely used configuration today.

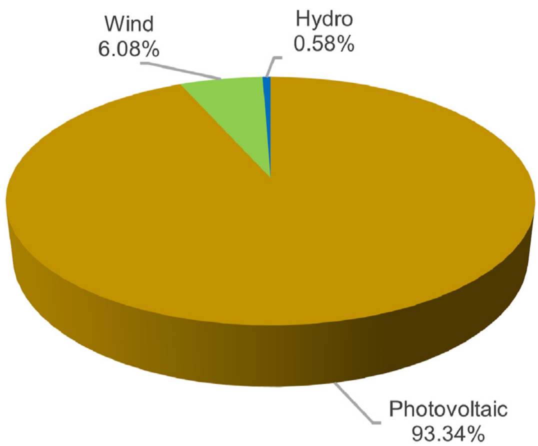


Fig. 11 – Percentage contribution of RES to green H_2 production in Paraguay. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Calculation of energy service cost (mobility)

The cost of mobility (C_M) FCHEBs was calculated in comparison to DICEBs and BEBs, the latter of which are already in use in the Metropolitan Area of Asunción. According to Ref. [74], C_M is calculated considering their investment cost (I_C, US$), driven distance per year (d, km/year), their energy cost (C_E, US$/km) and other operating and maintenance costs ($C_{O\&M}$, US$/km):

$$C_M = [(I_C \times CRF) / d] + C_E + C_{O\&M} \tag{8}$$

The capital recovery factor (CRF) is calculated depending on the discount rate (r) over the analyzed period (n):

$$CRF = [(1+r^n)\, r] / [(1+r)^n - 1] \tag{9}$$

The energy cost (C_E) is dependent on the average energy consumption of the buses (E_i) and the corresponding energy (diesel, H_2, and electricity) prices (P_{Ei}):

$$C_E = E_i \times P_{Ei} \tag{10}$$

In the case of FCHEBs, assuming that H_2 is stored on-board as a compressed gas, a compression system is necessary. The energy consumption for H_2 compression (E_{comp}) is calculated as:

$$E_{comp} = k_{cth} / \eta_c \tag{11}$$

where k_{cth} is the theoretical energy required for H_2 compression (kWh/kg$_{H2}$) and η_c the compressor efficiency. The theoretical specific energy for H_2 compression, k_{cth}, is defined as the energy required for compressing 1.0 kg of H_2 from the electrolyzer pressure, P_i (also considered to be the compressor's inlet pressure), to the maximum storage pressure, P_o (also considered to be the compressor's outlet pressure). Since H_2 is heated during the compression process, adiabatic rather than isothermal compression [75] is assumed to calculate the power required for H_2 compression:

$$P_{adiab} = M_f\, RT \times \left(\frac{\gamma}{\gamma-1}\right) \times ln\left[\left(\frac{P_o}{P_i}\right)^{(\gamma-1)/\gamma} - 1\right] \tag{12}$$

In this study it was assumed a H_2 refueling station (HRS) of 500 kg$_{H2}$/day. This HRS can attend a fleet of 16 FCHEBs with the following technical specifications in Table 15.

In this context, the flow rate of 31.25 kg$_{H2}$/h is equivalent to 4.34 mol/s, eq. (12) can be modified to give the theoretical specific energy for H_2 compression, k_{cth} (in kWh/kg$_{H2}$) for 100% efficient adiabatic compression:

$$k_{cth} = 4.34RT \times \left(\frac{\gamma}{\gamma-1}\right) \times ln\left[\left(\frac{P_o}{P_i}\right)^{(\gamma-1)/\gamma} - 1\right] \tag{13}$$

with the following assumptions used in this work: $T = 298$ K and $\gamma = 1.42$. Compression is evaluated at 298 K in this study because temperature can otherwise have a substantial effect on the energy requirement for compression. Overall, the evaluation of k_{cth} in this study is considered to be a conservative approximation since it assumes all H_2 needs to be compressed to the maximum pressure, and the formula used is for single-stage compression, which is typically less efficient than a more likely multi-stage compression. This is counterbalanced to a lesser extent by the treatment of H_2 as a perfect gas, which is quite accurate for intermediate pressures. In this study, it has been assumed that H_2 produced on-site from a PEM electrolyzer is at 30 bar (P_i) and FCHEBs are refueled with H_2 at 350 bar. The compression system is a mechanical diaphragm compressor capable of increasing the H_2 pressure up to 500 bar (P_o) to later reach the pressure required in the FCHEB tank at 350 bar. The parameters directly affecting the energy consumption for H_2 compression and storage are listed in Table 16.

As the compressor efficiency is expressed in terms of adiabatic compression (cf. eq. (13)), the upper limit of 100% considered is not unrealistic since the energy requirement for multi-stage compression, which is used in practice, is expected to be less than for single-stage adiabatic compression. This calculation is limited to the compression of H_2 to store it onboard FCHEBs, excluding H_2 production and dispensing equipment.

Table 14 – Reported H_2 production potential from renewable resources.

Country, region	H_2 (ton/year)	Ref.	Country, region	H_2 (ton/year)	Ref.
Argentina, Córdoba	37.3×10^3	[59]	Brazil (STE)	3.2×10^6	[71]
Brazil, Ceará	5.1×10^3	[52]	Nepal (STE)	140×10^3	[72]
USA	20.7×10^6	[69]	USA (wind)	1.1×10^{12}	[47]
Ecuador, Azuay	10.8×10^3	[70]	USA (PV)	8.7×10^9	[47]
Ecuador	4.55×10^5	[40]	USA (STE)	1.0×10^6	[44]
Argentina	1.0×10^{12}	[48]	Paraguay	22.5×10^6	This study
Venezuela	20.7×10^6	[55]			

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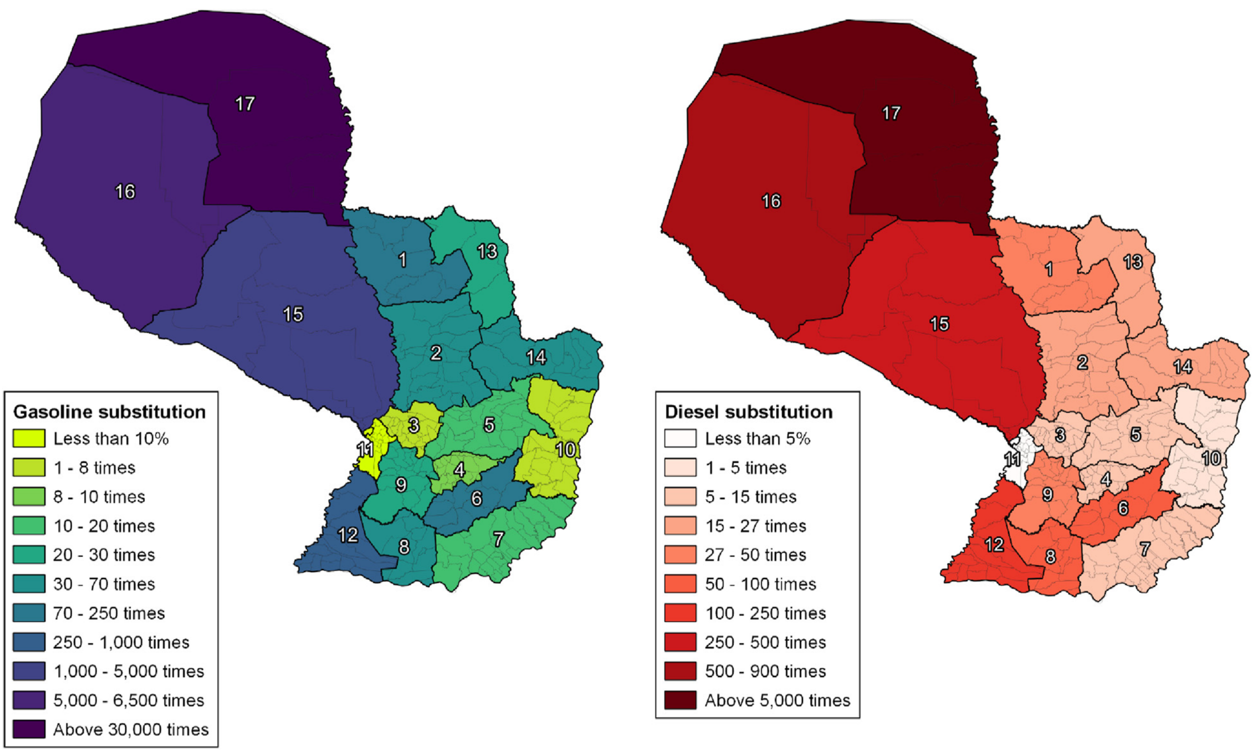

Fig. 12 – Green H_2 production potential relative to gasoline and diesel consumption, by department in Paraguay. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

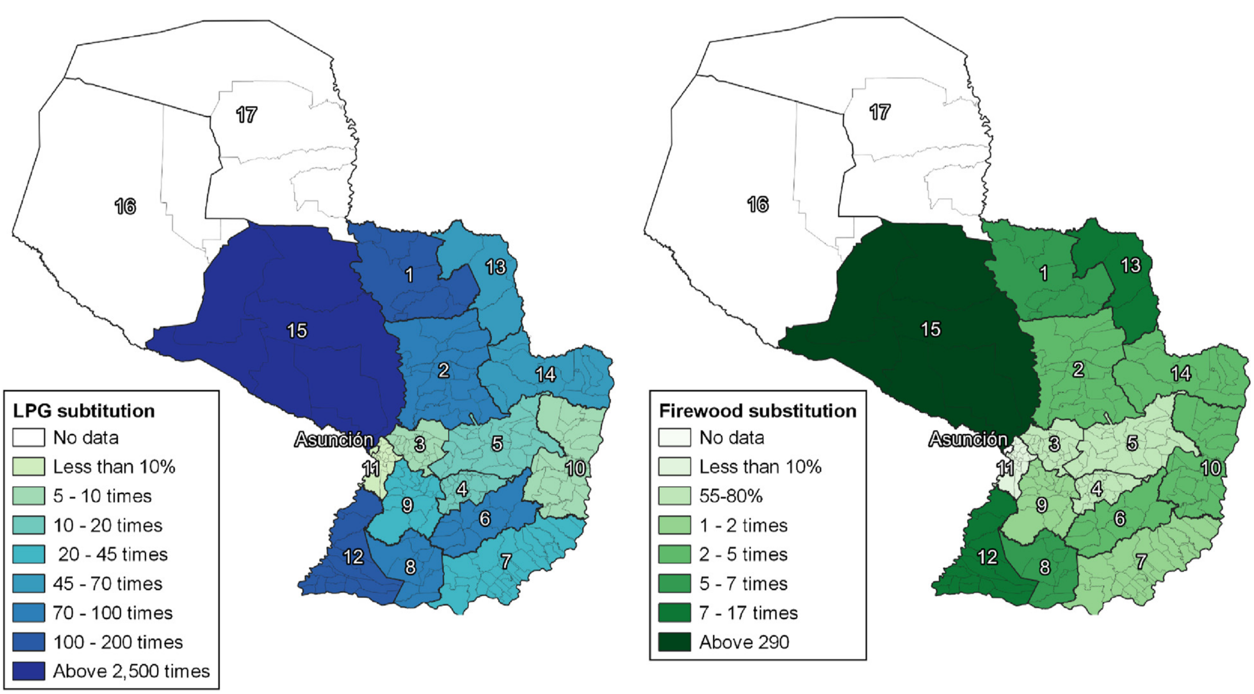

Fig. 13 – Green H_2 production potential relative to firewood and LPG consumption, by department in Paraguay. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Considering a HRS of 500 kg_{H2}/day, the power required for H_2 compression is approximately 12.6 kW. As reported by Ref. [76], H_2 dispensing adds approximately US$ 2/kg_{H2} to the cost of 1.0 kg of H_2, assuming industrial electricity rates of US$ 0.030/kWh and a HRS of 500 kg_{H2}/day with 20 years of amortization.

According to Ref. [78], if H_2 gas is initially generated at 20 bar, the lowest possible energy to compress H_2 isothermally in a single stage from 20 bar to 350 bar at 20 °C is 1.08 kWh/kg_{H2}, while the energy to compress from 20 bar to 700 bar is 1.48 kWh/kg_{H2}. Due to compressor inefficiencies and leaks, higher compression energies are required to achieve these high pressures in practice. The United States Department of Energy's (DOE) Technology Validation Project data for compression from on-site H_2 production ranges from 1.7 kWh/kg_{H2} to 6.4 kWh/kg_{H2}, depending on inlet, outlet pressures and compressor efficiency [79].

The labor costs for the drivers are not included in this calculation since these costs are the same for all bus types analyzed. In our base case, it was calculated using the current Paraguayan energy price data [80,81]. In this study, it was calculated with the exemptions of registration and value-added tax. FCHEB range was found to be comparable with the typical DICEB in Paraguay. The current generation of FCHEBs can operate long daily shifts of 330 km/day in revenue service without the need to be refueled [76]. The main characteristics of the bus, such as energy consumption, costs, among others, were taken from literature [74,82]. Major input data and assumptions for calculations are given in Table 17.

For the three bus types analyzed, the mobility cost of the bus is depicted in Fig. 14. From these results, it can be concluded that the major barriers to the faster penetration of FCHEBs are their high costs in comparison to conventional DICEBs. It is obvious that the investment cost of FCHEBs is far away from the possible competitiveness with DICEBs as well as with BEBs. Despite their high investment costs, FCHEBs have very competitive fuel costs due to low H_2 prices in Paraguay. In addition, the operating and maintenance costs of the FCHEBs are similar to those of DICEBs and BEBs.

Although the economic assessment clearly shows that, currently, FCHEBs are not competitive with conventional DICEBs as well as with BEBs, they have some environmental advantages that make them interesting for the future mobility system in Paraguay. As reported by Ref. [74], in the future, this could be reduced by harvesting technological learning effects. It can be expected that technological learning and economies-of-scale will bring down the cost of the FCHEBs. By 2027, the total costs of BEBs could be lower than those of DICEBs, and by 2050, the total costs of all bus technologies analyzed could be in a similar range. Due to the high purchase prices of the FCHEBs, the impact of green H_2 prices in Paraguay (US$ 5.74/kg_{H2}) on total mobility costs is relatively low.

Table 15 – Technical specifications of FCHEBs.

Parameter	Units	Value	Ref.
Bus length	m	12–14	[76]
Specific H_2 consumption	kg_{H2}/100 km	9.1	[74,76]
Full H_2 tank capacity	kg	30	[76]
H_2 storage pressure	bar	350	[76]
Driven distance with one full H_2 tank	km	330	[76]
Availability	days/year	285	[74]
Lifetime	hours	25,000	[76]

Environmental aspects and calculation of CO_2 emissions

According to Art. 7 of Law N° 294/93 "On Environmental Impact Assessment" and its regulations, Decree N° 453/13 and its modification and expansion Decree N° 954/13, the future implementation, execution, and operation of a fleet of buses with FCHEB and BEB technologies in Paraguay represents an activity that, due to its size or intensity, is likely to cause possible alterations to the environment surrounding its location and the potential effects of the activities foreseen in the design and their consequences on components of the physical, biological, socioeconomic, and cultural environment. For this purpose, the sources of impacts to the soil, water, air, visual landscape, flora, fauna, safety, and occupational health are individualized, which will allow establishing measures with which negative impacts can be prevented and/or mitigated, as well as the enhancement of those positive impacts with their respective costs and implementation schedule. The monitoring program for the implementation of mitigation measures for the identified environmental impacts is defined.

Regarding the environmental impact related with air quality, it was calculated with a CO_2 emission factor of 0.7 $kgCO_{2eq.}$ per kg H_2 at nozzle [84]. The CO_2 emission factor of electricity for BEBs strongly depends on the electricity mix. Table 18 shows the CO_2 emission factors used in this study. Since FCHEBs and BEBs have zero emissions at the point of use, the Tank-To-Wheel emissions are only relevant for DICEBs.

Finally, CO_2 emissions over the lifespan (n) of the buses depend on the level of travel activity (d), the average energy consumption of the buses (E_i), and the carbon content (emission factor e_{CO2}) of the energy used (f_{CO2}). The relationship between these parameters is represented mathematically by eq. (14):

$$e_{CO_2} = E_i \times d \times n \times f_{CO_2} \qquad (14)$$

The focus was put on Well-To-Wheels (WTW) CO_2 emission analyses. This approach differs from a Life Cycle Analysis (LCA), as it does not consider energy and emissions involved in building facilities and vehicles, or emissions related to their end of life. The WTW analysis focuses on lifetime energy use and corresponding greenhouse gas (GHG) emissions. Fig. 15 shows, in comparison, the CO_2 emissions of standard 12-m buses. It compares DICEBs, FCHEBs, powered by green H_2, and BEBs powered with hydroelectricity.

It can be noted that FCHEBs driven with green H_2 have the potential to save about 96% of CO_2 emissions in comparison to DICEBs. FCHEBs and BEBs are considered environmentally friendly technologies and demonstrate significant mitigation of the environmental impact generated by DICEBs on urban air quality through the effective implementation of green H_2 in Paraguay. Besides, according to Ref. [74], their environmental impact is very dependent on the primary energy sources used for electricity generation and H_2 production. In this analysis, the emissions caused during bus manufacturing and maintenance are not included. However, emissions from fuel production and bus operation have an overwhelming impact on total bus emissions [84]. The electrolyzers use only water as raw material, and by means of energy, carry out the

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Table 16 – Parameters used to calculate the energy consumption for H_2 compression.

Parameter	Units	Value	Ref.
Compression system type	mechanical diaphragm compressor		[76]
Compressor efficiency (η_c)		75%	[77]
Electrolysis pressure (also inlet pressure to compressor) (P_i)	bar	30	[76]
Outlet pressure from compressor (P_o)	bar	500	[76]
H_2 compression system availability	h/day	16	[76]

Table 17 – Major input data and assumptions for the C_M calculation.

Assumptions	DICEB	Ref.	FCHEB	Source	BEB	Ref.
Discount rate	8%	[83]	8%	[83]	8%	[83]
Analyzed period (year)	14	[74]	14	[74]	14	[74]
Driven distance (km/year)	94,050	[76]	94,050	[76]	94,050	[76]
Driven distance (km/day)	330	[76]	330	[76]	330	[76]
Energy price	1.41 US$/L	[80]	5.74 US$/$kg_{H2}$ [a]	[76]	30 US$/MWh	[76]
Specific energy consumption	35 L/100 km	[74]	9.1 kg_{H2}/100 km	[74,76]	2.58 kWh/100 km	[82]
O&M cost (US$/km)	0.31	[74]	0.27	[74]	0.23	[74]
Investment cost (US$)	110,000	[82]	715,000	[74]	325,000	[82]
Results: mobility cost	0.945	US$/km	1.709	US$/km	0.727	US$/km

[a] This value includes H_2 production, compression, storage, and dispensing costs [76].

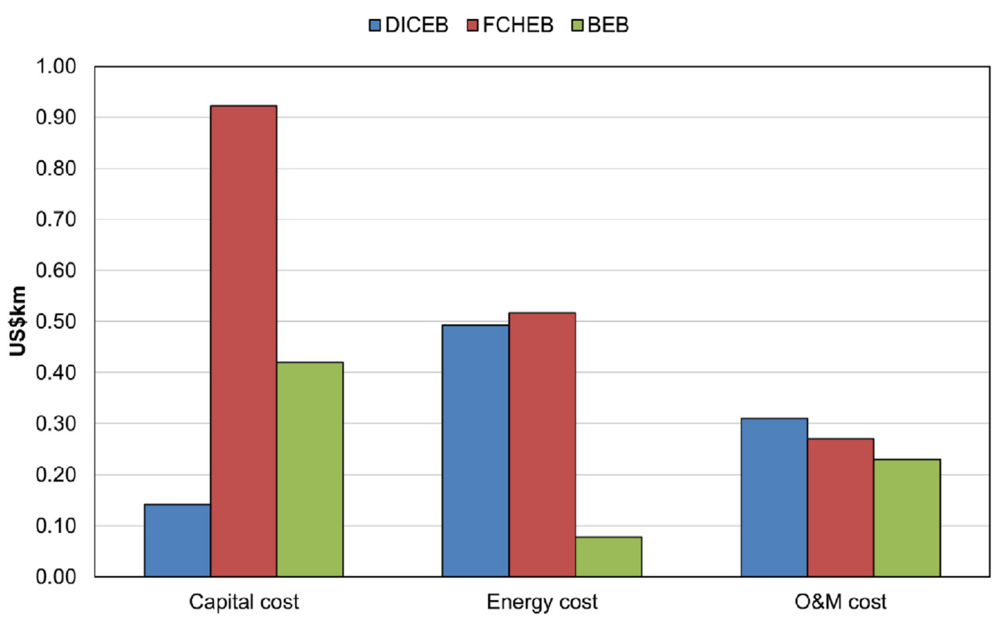

Fig. 14 – Mobility cost using DICEBs, FCHEBs and BEBs in Paraguay.

electrolysis of the molecule without generating any harmful contaminants. Approximately, for every 1.0 m^3 used in osmosis, 0.9 L of water is obtained with sufficient quality for electrolysis, but the rejection of this process is water that does not require treatment for discharge and is completely harmless. Therefore, harmful emissions are null during the operational phase. There are no mobile parts in the hydrogen production process. This equipment is very reliable and operates quietly. Catalysts are a significant source of environmental impact in electrolysis at the mining level, owing to contamination caused from the use of Ni and Pt, among other metals. Because of the materials used in their manufacture, such as fluorine-derived compounds for the membrane and noble metals, PEM technologies are more likely to have a bigger environmental impact [76].

Quality of life, SDGs, water quality and green H_2

Quality of life can be conceived as the scope of a state of human well-being. Although it is a concept with a certain degree of subjectivity, mechanisms and instruments have been proposed for its assessment that consider economic, social, environmental, health, and cultural factors. The Quality of Life Index is one of them, and it employs an estimating methodology that includes dimensions and indicators linked with each of the criteria described [88].

Table 18 – CO_2 emission factors of different fuel types.

Fuel type	CO_2 emission factor	Source
Diesel	3.13 $kgCO_{2eq.}/L_{diesel}$ = 86.5 $kgCO_{2eq.}/GJ_{diesel}$	[85,86]
Green H_2	0.7 $kgCO_{2eq.}/kg_{H2}$ = 5.8 $kgCO_{2eq.}/GJ_{H2}$	[84]
Electricity Paraguay	0.024 $kgCO_{2eq.}/kWh_{el}$ = 6.7 $kgCO_{2eq.}/GJ_{el}$	[87]

Among the relevant dimensions for the purpose of this study are housing, the environment and health, with the respective indicators; availability of services, quality of the environment and life expectancy at birth. As a result, the use of green H_2 as a cooking fuel and an input for electricity generation in rural households in Paraguay impacts all the mentioned indicators, increasing the population's quality of life index. Thus, the impact of substituting firewood with clean fuel on household health has been widely studied [89].

Alternatively, the Human Development Index has been formulated that considers the dimensions of health, education, and income, also analyzed in several publications [90]. In this regard, the National Report on Human Development of Paraguay indicates that energy is a fundamental resource to promote human development, emphasizing the use of sustainable and clean energy sources as mechanisms to face two challenges: climate change and human development based on equal opportunities [91].

The Sustainable Development Goals (SDG) were approved in 2015, whose fundamental purpose is to overcome poverty, protect the planet, and improve human society's quality of life [92]. In this sense, the range and scope of the H_2 uses proposed are in line with and contribute to the attainment of numerous of the SDGs to varying degrees. Thus, in Goal 3: Guarantee a healthy life and promote well-being for all and at all ages; Goal 8: Promote inclusive and sustainable growth; Goal 9: Build a resilient infrastructure, promote sustainable industrialization, and foster innovation; Goal 10: Reduce inequality within and between countries; 11th Goal: Make cities more inclusive, safer, resilient, and sustainable.

Special mention for Goal 7: Guarantee access to affordable, safe, sustainable, and modern energy. Due to its properties, production routes, and use, H_2 is aligned with the goals of this objective: 7.1. Guarantee universal access to affordable, reliable, and modern energy services, and the Goal 7.2. Considerably increase the proportion of renewable energy in all energy sources. Also in Goal 13: Adopt urgent measures to combat climate change and its effects. H_2 plays an important role in its compliance from its final uses as a fuel with low impact on GHG emissions. All of H_2's contributions to the achievement of the SDGs have been discussed in depth in Ref. [93] and mentioned in Ref. [11].

Water quality, the efficient use of water resources, and the sustainability of drinking water supply are contained in SDG 6: Clean water and sanitation. Particularly in the 6.3 and 6.4 objectives. The causal relationship between energy generation and water resource management is bidirectional, hence the ideal condition is an integrated resource management that minimizes both energy intensity in the water management, and water intensity in energy production and use. Related to water intensity, green H_2 production by water electrolysis has been regarded as a barrier or challenge to overcome in order to guarantee the sustainability of the process [4]. In Ref. [13] an alternative based on the use of seawater for electrolytic H_2 production is presented, in order to contribute to the preservation of water resources in a prospective scenario of intensive green H_2 use by 2050. As stated by [7], the electrolytic route of H_2 production has the smallest water footprint, 9 kg_{H2O}/kg_{H2}, compared to several processes based on fossil energy sources: natural gas with carbon capture, 13–18 kg_{H2O}/kg_{H2}, and coal gasification, 40–85 kg_{H2O}/kg_{H2}, depending on the water consumption in mining coal. Ref. [7] also estimated that, in a 2050 scenario, 7–9 billion m^3/year of water consumption would be equivalent to 0.25% of

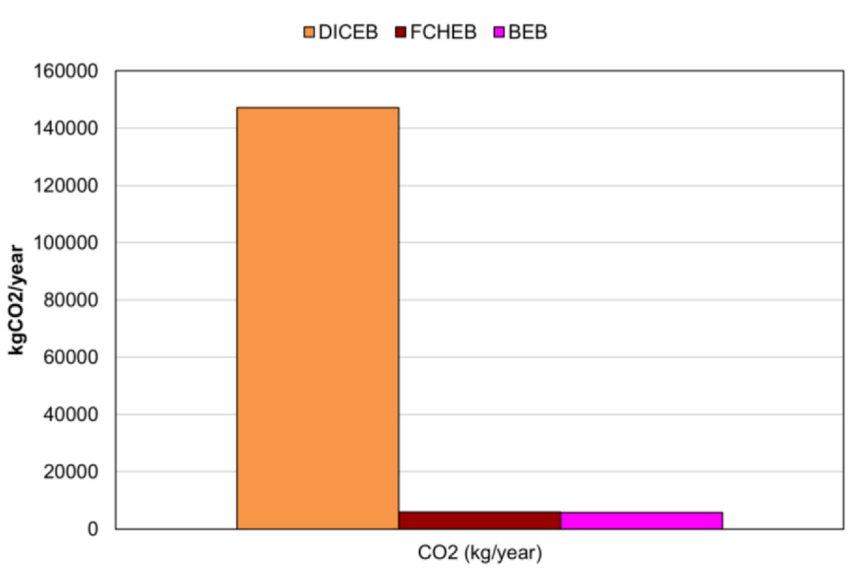

Fig. 15 – CO_2 emissions of different standard 12 m buses with 94,050 km driven per year.

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current freshwater consumption (4035 billion m^3) in four main consumption sectors: agriculture, industry, urban, and desalination processes. However, it is also pointed out that 85% of the projects formulated up to the year 2020 could require the intensive use of water desalination systems, increasing the total cost of H_2 production, but encouraging the advancement of desalination technologies and directing the consumption of fresh water to other sectors of society and contributing to the sustainability of the process and the water resource. In summary, on everything considered regarding the relationship between the production and consumption of green H_2 and the SDGs, a favorable impact can be conjectured across several of them that, ultimately, have a positive impact on improving the population's quality of life. This requires the creation of public policies and strategies to ensure that this impact effectively drives sustainable development instead of slowing it down or eventually delaying it.

Conclusion

From the preliminary assessment of green H_2 production potential in Paraguay, it is concluded that this energy carrier could constitute a suitable mechanism for improving the quality of life of people, particularly in rural areas, while contributing to a favorable change in the country's energy mix.

The incorporation of green H_2 also means reducing consumption of imported fossil fuels for the transportation sector and the resulting environmental pollution, especially in these cities: Asunción, Ciudad del Este, and Encarnación. The Project is feasible from the socio, environmental and economic approach, because the potential negative impacts can be adequately mitigated with the application of environmental measures, and it represents a potentially positive social and economic aspect because it contributes to improving the quality of life of the inhabitants that generates sources of employment safeguarding the quality of natural resources.

These results represent a starting point for more elaborate and exhaustive studies, including economic, social, and environmental aspects, especially in those departments where the results indicate high green H_2 potential and opportunities for its use.

Besides, it is very important to emphasize that resource availability is not the only factor to consider in assessing the likely locations for green H_2 production in Paraguay. Other important factors include distribution infrastructure and water availability.

Finally, this research demonstrates that the incorporation of the Hydrogen Economy in Paraguay is an ideal route to meet the national objectives of advancing the decarbonization of its economy, the energy transition, and compliance with the SDGs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Financial support from CONACYT (Consejo Nacional de Ciencia y Tecnología del Paraguay) through the project “Electrolytic hydrogen production potential from renewable energy sources in Paraguay" (PINV18-41) is gratefully acknowledged.

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Please cite this article as: Posso F et al., Towards the Hydrogen Economy in Paraguay: Green hydrogen production potential and end-uses, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.05.217

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Nomenclature

Acronyms

ANDE: National Administration of Electricity
AEL: Alkalyne Electrolyzer
BEB: Battery electric bus
DICEB: Diesel internal combustion engine bus
CF: Capacity factor
FCHEB: Fuel cell hybrid electric bus
GHG: Greenhouse gas
HHV: Higher heating value
HRS: Hydrogen Refueling Station
INE: National Institute of Statistics
IRENA: International Renewable Energy Agency
LAC: Latin America and the Caribbean
LHV: Lower heating value
LPG: Liquefied petroleum gas (cooking gas)
MADES: Ministry of Environment and Sustainable Development
MIC: Ministry of Industry and Commerce
PEM: Proton Exchange Membrane Electrolyzer
PETROPAR: Paraguayan Petroleums
PV: Photovoltaic
RES: Renewable energy sources
SDG: Sustainable Development Goals
SIEN: National Energy Information System
STE: Spilled turbinable energy
STC: Standard Test Conditions
USA: United States of America
VMME: Vice-Ministry of Mines and Energy
WTW: Well-To-Wheels

Parameters

F_{AP}: Percentage of the available area in each department of Paraguay
P_D: Population density (people/km^2)
η_{fv}: Photovoltaic conversion
η_e: H_2 production rate (kWh/kg_{H2})
I_{PA}: Average total annual insolation by department (kWh/m^2·year)
A_d: Department area (km^2)
D_F: Derate factor for photovoltaic installations
f_d: Availability factor
f_{lat}: Latitude incidence factor
$f_{shading}$: PV shading factor
f_{serv}: Area for servicing factor.
E_D: Electricity available for H_2 production (kWh/year)
M_f: Gas mass flow rate (mol/s)
R: Gas constant (8.3144 J/mol·K)
T: Temperature (K)
P_i: Inlet pressure to compressor (W)
P_o: Outlet pressure (W)
γ: Ratio of specific heats for the compressed H_2

Variables

E_{FV}: Photovoltaic electricity (kWh/year)
P_{H2}: Annual H_2 production (kg_{H2}/year)
$P(v_{air})$: Power obtained as a function of air speed (kW)
$E_{gridcell}$: Total energy produced by the grid cell in a given period (MWh)
C_M: Cost of mobility (US$/km)
e_{CO2}: CO_2 emissions (kg_{CO2}/year)