Toward the Hydrogen Economy in Paraguay: End-Uses of Green Hydrogen Potential

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1 Introduction

The hydrogen economy represents an innovative energy infrastructure with hydrogen destined to meet the energy needs of most sectors of society. Thus, hydrogen is obtained from renewable energy sources, stored, transported, and distributed in demand centers for its final conversion into useful energy [1]. Hydrogen generated in this way is known as green hydrogen and it is produced by water electrolysis, with the required electricity from renewable energy sources, and it is perceived as the best technical and economic prospects in the medium term [2]. Currently, the hydrogen economy has aroused exceptional interest to promote global and national economic recovery, energy decarbonization, and sustainable development in a post-SARS-CoV-2 (COVID-19) pandemic scenario [3].

Green hydrogen offers a diversity of potential uses. While direct electrification using renewable energy and energy efficiency is the most efficient path to reducing emissions in easier to abate sectors, green hydrogen can be an important option in the decarbonization of harder to abate sectors where direct renewable electrification is not technically feasible or would take too long time. The objective of this study was

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to identify end-uses of green hydrogen production potential in Paraguay. To accomplish this objective, two sectors of the Paraguayan economy were analyzed: residential and transportation.

2 Methodology

Methodologically, considering the potential for hydrogen production from key renewable resources (solar PV, wind, and hydro) in Paraguay [4], end-uses are focused on two sectors already identified as potential niche opportunities: transportation and residential. In the first sector, it was proposed to replace gasoline and diesel with green hydrogen since the energy equivalence between these fuels. At present, Paraguay counts 1.6×10^6 vehicles of which 7.7×10^5 are light vehicles [5]. In the residential sector, it is intended to replace firewood and LPG with green hydrogen as a heat source for cooking. Firewood is an inefficient and polluting energy source for cooking, and LPG is totally imported from Bolivia and Argentina. Charcoal consumption was not considered in this study because in Paraguay this sector is quite informal, without reliable data and unwilling commercial consumers and industrial companies to share consumption and price data.

The calculation method is like that used by [6]. For example, it is considered the following hypothetical case:

Gasoline consumption in the transportation sector in department A: 100 t/year.
Diesel consumption in the transportation sector in department A: 100 t/year.
Firewood consumption in the residential sector in department A: 100 t/year.
LPG consumption in the residential sector in department A: 100 t/year.
Green hydrogen production potential in department A: 30 t/year.

Then:

Hydrogen consumption equivalent to gasoline consumption: 90 t/year.
Hydrogen consumption equivalent to diesel consumption: 87.6 t/year.
Hydrogen consumption equivalent to firewood consumption: 12.6 t/year.
Hydrogen consumption equivalent to LPG consumption: 42 t/year.

$$Substitution(\%) = \left(\frac{H_2\ production\ potential}{H_2 equivalent\ consumption}\right) \times 100 \quad (1)$$

For gasoline: $(30/90) \times 100 = 33.3\%$.
For diesel: $(30/87.6) \times 100 = 34.2\%$.
For firewood: $(30/12.6) \times 100 = 238\%$.
For LPG: $(30/42) \times 100 = 71\%$.

3 Estimation Method of H_2 Consumption Equivalent to Gasoline and Diesel Consumption in Each Department

This study was conducted to estimate the amount of gasoline and diesel consumption that could potentially be displaced by green hydrogen in each department of Paraguay. In 2020, gasoline and diesel consumption in Paraguay was 6.9×10^5 t and 1.6×10^9 t, respectively [7]. Gasoline and diesel consumption data for 2018 were obtained from the Ministry of Industry and Commerce (MIC) as seen in Table 1.

As shown in Table 1, the most populated departments of Paraguay are Central, Alto Paraná, and Itapúa, present the highest gasoline and diesel consumptions.

The replacement is based on the energy equivalence between hydrogen, gasoline, and diesel and on gasoline and diesel consumption in each department. Thus, the lower heating value (LHV) the density for gasoline, diesel [8] and hydrogen are [10]:

Gasoline:

LHV: 9.04 kWh/L
Density $= 814$ kg/m^3

Diesel:

Table 1 Gasoline and diesel annual consumption in each department of Paraguay

Department	Gasoline consumption ($\times 10^3$ m^3/year)	Diesel consumption ($\times 10^3$ m^3/year)
Distrito Capital	49.5	57.6
Concepción	12.3	16.6
San Pedro	176	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

Source: [8]

LHV = 10.07 kWh/L
Density = 884 kg/m^3

Hydrogen:

LHV = 33.3 kWh/kg
Density at STP = 0.09 kg/m^3

Then, the relation presented in Eq. 2 shows the equivalence between different fuels:

$$1\ kg\ H_2 = 3\ kg\ Gasoline = 2.92\ kg\ Diesel \quad (2)$$

3.1 Estimation Method of H_2 Consumption Equivalent to Firewood and LPG Consumption in Each Department

In the residential sector, it is proposed to replace firewood and LPG with green hydrogen as a heat source for cooking. At first, firewood and LPG residential consumption in each department was calculated. Then, energy equivalence between firewood, LPG, and electrolytic hydrogen, based on the LHV, was calculated in order to determine the electrolytic hydrogen amount required for each department of Paraguay. Several studies show a wide range in the consumption per capita of firewood in Paraguay. Firewood consumption in Paraguayan homes is 2.86×10^6 t [11]. According to [12], this consumption was 2.6×10^6 t in 2005. There are various values from different studies, which vary between 0.6 and 8.0 t/inhabitant/year, for different sites in the Eastern Region of Paraguay [13]. Regarding the mentioned data, "not all the information is officially registered in statistical sources, the real figure for firewood consumption should be a lot higher," and total firewood production is approximately 7.5×10^6 t that includes firewood for charcoal production. According to [13], 65% (4.875×10^6 t) is used for self-consumption. Firewood consumption in households is approximately 10–15 t/household/year [14]. This consumption is very high compared to other countries, but it is explained by the inefficient use of firewood: traditional cooking in the oven (Tatacua) and the permanent use of firewood in rural households. Consumption of firewood in rural households varies between 10 and 15 t/household/year [15]. Firewood consumption in households in Paraguay is approximately 1.8–2.7 t/inhabitant/year considering four members per household [9].

To calculate firewood consumption in Paraguayan households, it was used official statistical data [16]. In 2020, LPG consumption in Paraguay was 8.7×10^4 t [7]. According to [17], Paraguay's average LPG consumption is approximately 7.5×10^3 t/month. In Paraguay, LPG is totally imported, 80% from Bolivia and 20% from Argentina. In July 2021, the importation cost was US$ 0.54/

Table 2 Considered values to estimate firewood and LPG consumption in households for cooking in Paraguay

Parameter	Value	Unit	Source
Household	4	Members	[8]
Average firewood consumption	12.5	t/household/year	[14]
Average LPG consumption	0.18	t/household/year	[16]

Table 3 Firewood and LPG consumption by department, annual average from 2017 to 2019

Department	LPG ($\times 10^3$ t/year)	Firewood ($\times 10^3$ tn/year)
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.	n.d.a.
Alto Paraguay	n.d.a.	n.d.a.
Paraguay	179.6	5216.6

Source: [17]
n.d.a. = no data available

kg LPG. Finally, Table 2 shows the values considered in this study to estimate firewood and LPG consumption in households for cooking in Paraguay.

Table 3 shows firewood and LPG consumption by department, annual average from 2017 to 2019.

As shown in Table 3, the highest demand for firewood corresponds to the rural residential sector. Currently, in Paraguay**,** firewood consumption is higher than production, and firewood sources are diminishing due to deforestation. Regarding the urban residential sector, it can be seen in Table 3 that LPG is the main fuel for cooking. According to [7], more than 3.0×10^4 households do not use firewood for cooking anymore in 2020 compared to 2019.

The replacement is based on the energy equivalence between hydrogen, firewood, and LPG and on firewood and LPG consumption of each department of Paraguay.

Thus, the lower heating value and density for hydrogen [10] and for firewood and LGP [9] are:

Firewood (20% moisture):

LHV: 4187 kWh/t
Density: 768.8 kg/m^3;

LPG:

LHV: 14 MWh/t
Density: 550 kg/m^3

Hydrogen:

LHV: 33.3 kWh/kg
Density at STP: 0.09 kg/m^3

The equivalence between fuels is presented in Eq. 3.

$$1\ kg\ H_2 = 2.38\ kg\ LPG = 7.95\ kg\ Firewood \tag{3}$$

4 Results

4.1 Renewable Hydrogen Potential Relative to Gasoline and Diesel Consumption by Department in Paraguay

Table 4 shows gasoline and diesel consumption that could potentially be displaced by green hydrogen in each department of Paraguay.

Considering the energy equivalence between gasoline, diesel, and hydrogen, it was verified that the Capital District and the Central department, the latter the most populated department of Paraguay, cannot produce enough hydrogen from renewable resources to completely displace their high gasoline and diesel consumption. However, they could rely on hydrogen from surrounding departments. In the Capital District and the Central department, renewable hydrogen could displace 3% and 52% of their gasoline and diesel consumption, respectively. According to Table 4, Fig. 1 shows renewable hydrogen production potential relative to gasoline and diesel consumption, by department in Paraguay.

According to Fig. 1, departments in the Western region, because of their relatively low gasoline and diesel consumption and high amounts of renewable solar and wind resources, have the potential to displace more than 5×10^3 times their current gasoline demand. As mentioned above, only the Capital District and the Central department cannot produce enough renewable hydrogen to completely displace their high gasoline and diesel consumption.

Table 4 Green hydrogen potential relative to gasoline and diesel consumption by department in Paraguay ($\times 10^3$ t/year)

Department	Gasoline + diesel	Equivalent H_2 production	H_2 production potential	Substitution %
Distrito Capital	91.2	30.9	0.9	3
Concepción	24.7	8.4	3996.1	47,813
San Pedro	36.4	12.3	3373.1	27,343
Cordillera	25.1	8.5	456.4	5370
Guairá	15.3	5.2	356.8	6902
Caaguazú	53.8	18.2	1218.8	6682
Caazapá	8.1	2.7	1568.9	57,392
Itapúa	61.5	20.8	1931.9	9258
Misiones	11.2	3.8	1992.9	52,586
Paraguarí	14.1	4.8	1196.7	25,187
Alto Paraná	131.0	44.4	1494.3	3365
Central	275.9	93.5	48.9	52
Ñeembucú	5.2	1.7	3554.8	203,083
Amambay	38.8	13.1	2959.8	22,591
Canindeyú	47.5	16.1	3017.3	18,710
Presidente Hayes	22.9	7.8	52526.1	673,859
Boquerón	38.0	9.6	111750.8	1,169,046
Alto Paraguay	7.0	2.4	202723.8	8,486,890
Paraguay	897.8	304.2	394168.4	129,573

4.2 Renewable Hydrogen Potential Relative to Firewood and LPG Consumption by Department in Paraguay

Table 5 shows firewood and LPG consumption that could potentially be displaced by renewable hydrogen potential in each department of Paraguay.

LPG is getting popular with its convenience and clean burning in use compared to firewood in urban areas. Firewood is mostly used as a cooking fuel in rural areas where people have no access to LPG. According to Table 5, Fig. 2 shows firewood and LPG consumption substitution percentage with renewable hydrogen for the residential sector in Paraguay. Fig. 2 shows renewable hydrogen production potential relative to firewood and LPG consumption, by department in Paraguay.

As shown in Fig. 2, it is possible to comprehensively satisfy firewood and LPG consumption in all departments of Paraguay with local renewable hydrogen production, except in Asuncion. The results of this analysis show that the Capital District and Central department cannot produce enough hydrogen from renewable resources to completely displace their high firewood and LPG consumption. However, they could, in most cases, rely on hydrogen from surrounding departments. Renewable hydrogen in the Capital District and Central department could displace

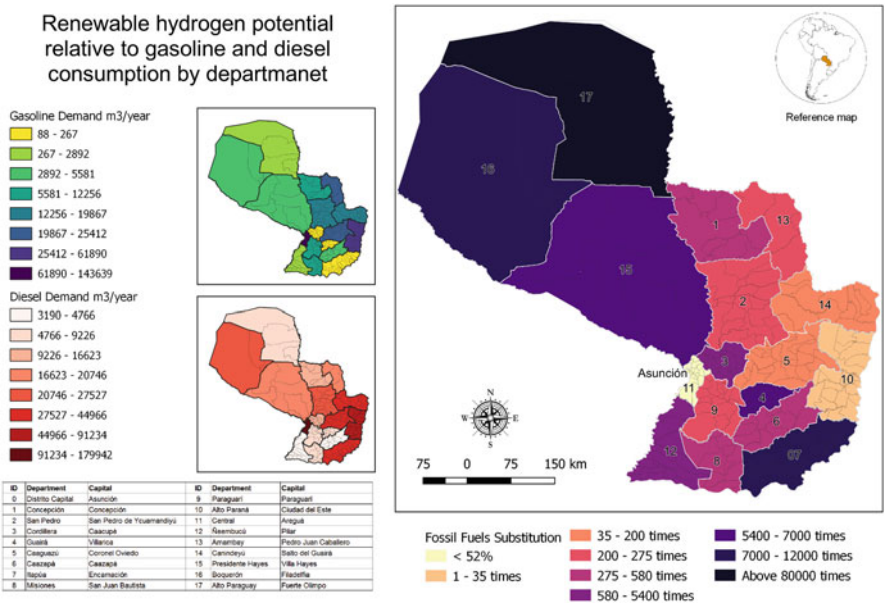

Fig. 1 Renewable hydrogen production potential relative to gasoline and diesel consumption, by department in Paraguay

Table 5 Renewable hydrogen potential relative to firewood and LPG consumption by department in Paraguay ($\times 10^3$ t/year)

Department	Firewood + LPG	Equivalent H_2 production	H_2 production potential	Substitution %
Capital District	155.0	24.5	0.9	4
Concepción	334.4	43.3	3996.1	9226
San Pedro	775.5	98.9	3373.1	3410
Cordillera	357.7	46.8	456.4	976
Guairá	343.6	44.3	356.8	806
Caaguazú	711.2	92.1	1218.8	1323
Caazapá	382.1	48.8	1568.9	3213
Itapúa	718.9	94.5	1931.9	2045
Misiones	143.0	19.0	1992.9	10,506
Paraguarí	527.1	67.4	1196.7	1775
Alto Paraná	377.5	56.0	1494.3	2667
Central	330.5	60.4	48.9	81
Ñeembucú	113.3	15.1	3554.8	23,556
Amambay	79.7	11.9	2959.8	24,785
Canindeyú	273.4	36.1	3017.3	8352
Presidente Hayes	81.6	11.1	52526.1	474,839
Boquerón	n.d.a.	n.d.a.	111750.8	–
Alto Paraguay	n.d.a.	n.d.a.	202723.8	–
Paraguay	5703.7	770.3	394168.4	51,170

n.d.a. = no data available

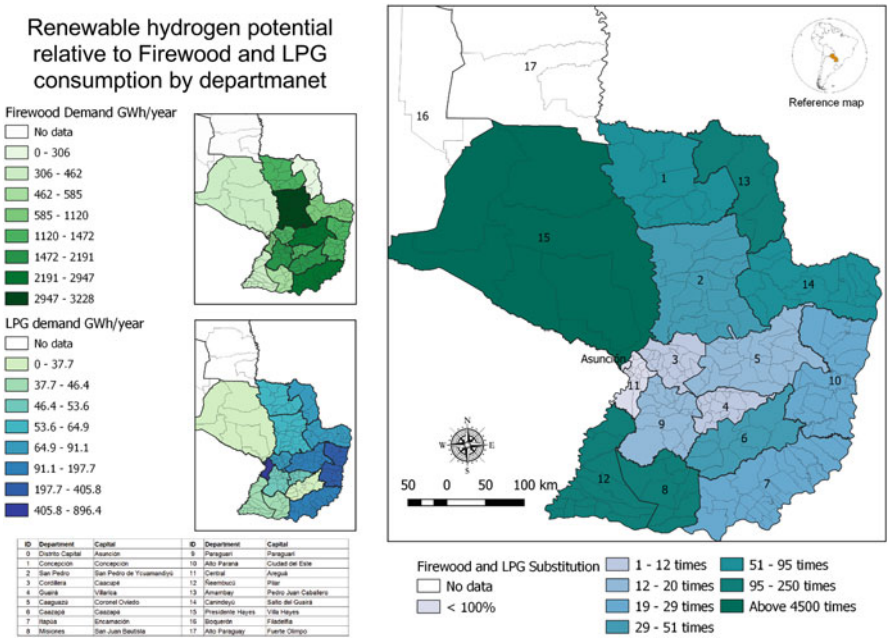

Fig. 2 Renewable hydrogen production potential relative to firewood and LPG consumption, by department in Paraguay

approximately 4% and 81% of their firewood and LPG consumption, respectively. In contrast, the Boquerón department in the Western region, because of their relatively low firewood and LPG consumption and high amount of renewable solar and wind resources, have the potential to displace more than 4.7×10^3 times their current firewood and LPG demand. The renewable hydrogen production surplus of each department can be used to generate electricity from PEMFC to supply 1.4×10^4 households that do not have this basic service in Paraguay. For calculations, it was assumed an electricity consumption of 3 MWh/household/year [16], and a typical household is composed of four people [18]. To generate electricity, it was considered a proton exchange membrane fuel cell (PEMFC) with an average efficiency of 53% [19], higher than the efficiency of an internal combustion engine. Results demonstrate that the green hydrogen production surplus of each department would satisfy this requirement in the whole country. The end-use technologies of hydrogen are known and commercially available, especially fuel cell electricity generation on a small scale. However, its adoption for specific situations requires a detailed technical and economic analysis, which supports decision-making and whose development is beyond the scope and purpose of this study.

5 Discussion

At present, Paraguay's 100% need of petroleum products such as gasoline, diesel, and LPG (cooking gas) is imported by paying the hard currency. These imported fossil fuels can be completely replaced by electrolytic hydrogen produced from domestic renewable energy sources. Obtained results envisage an optimal scenario for a future hydrogen economy in Paraguay. This will require financial investment from both public and private sectors for sustainable energy project development and the suitable infrastructure implementation for using renewable hydrogen as an energy carrier in the transportation sector. Furthermore, renewable energy sources geospatial distribution in Paraguay also implies an important opportunity for distributed generation advancement in energy policies, meaning greater decentralization, redistribution, self-sufficiency, and democratization of the energy system, and, consequently, greater regionalization of production and economy.

6 Conclusion

The results conclude that the green hydrogen production potential of Paraguay can meet 367 times firewood, LPG, gasoline, and diesel consumption in 2021. At present, Paraguay's 100% need of petroleum products such as gasoline, diesel, and LPG (cooking gas) is imported by paying the hard currency. These fossil fuels can be completely replaced by electrolytic hydrogen produced from solar, wind, and hydropower. Using green hydrogen as a fuel for vehicles not only saves money on import of fossil fuels but also reduces harmful emissions and carbon dioxide, improving the air quality significantly in most populated cities, for example, Asunción, Encarnación, and Ciudad del Este. According to the National Development Plan Paraguay 2030, Paraguay has proposed to reduce the consumption of fossil fuels by 20% and increase the consumption of renewable energy sources by 60% by 2030. This research demonstrates that hydrogen obtained from domestic renewable energy sources in Paraguay is a very attractive alternative to achieve mentioned national goals. Besides, green hydrogen could promote technological development and energy transition in Paraguay, not only in the transportation and residential sectors but also in industry and other sectors. Green hydrogen would be a 100% domestic fuel that would take advantage of large biomass, solar, wind, and hydro resources making a significant contribution to the value chain and the different productive sectors. Paraguay could take advantage of its strategic geographic location in the center of South America to become a logistics and green hydrogen hub.

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