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Green hydrogen assessment of generation and storage potential from solar and wind energy shedding in Honduras

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Abstract. Honduras relies on fossil fuels and reservoir hydroelectric power plants to maintain the stability of the national electrical network. Due to the intermittency of renewable resources, solar and wind power plants cannot provide stability to the national electrical network. Renewable plants in the country that use variable renewable resources such as wind and solar have energy shedding controlled by the National Dispatch Center of Honduras to maintain a safe electrical system. Energy shedding can be defined as non-generated energy as a result of power limitations in renewable plants. This energy shedding can be used for green hydrogen production, which can displace fossil fuel technologies, bring stability to the national electrical network, and contribute to the decarbonization process of the country. In this research, sixteen green hydrogen Power-to-Power plants were sized using cumulative energy generation curves built with energy shedding data held by the National Dispatch Center of Honduras. A cost-benefit analysis was used as a decision criterion for the sizing of the hydrogen plants. The annual green hydrogen and energy production by electrolyzers and fuel cells, and the potential for carbon dioxide emission mitigation was estimated. The energy return on investment of each plant was calculated to analyze the harnessed energy in the hydrogen system.Page layout

1 Introduction

Every country must have a stable and secure electrical system. This requires dispatchable power generation to control the balance between electrical load and power generation. Honduras depends entirely on thermal and reservoir hydroelectric generation to stabilize the national electrical network. Currently (2022) the installed capacity of thermal plants is 30% and 31.7% for hydroelectric plants [1]. If these plants decrease their percentage of participation, the stability of the national electrical network would be threatened.

Renewable energies such as solar and wind cannot provide stability to the grid because they do not have dispatchable generation. It is essential to mention that power generation plants that use variable renewable resources are affected by power limitations as a consequence of the variability of the resource they use or low national electrical demand. These power limitations that prevent the generation of energy at the maximum capacity of the plant are unavoidable since they are made to maintain the security of the national electrical network. The energy that was not generated due to power limitations is called "energy shedding" which can be used for green hydrogen production.

The carbon dioxide emitted into the atmosphere due to the process of fossil fuels energy generation has a negative impact on the environment, contributing to the greenhouse effect [2]. Carbon dioxide emissions in Honduras have increased by 38.25% from 2018 to 2020. In 2020, the power generation sector was responsible of 54% of the carbon dioxide emissions [3]. This research is intended to estimate the green hydrogen potential from solar and wind energy shedding to provide stability to the national electrical network and decrease carbon dioxide emissions in Honduras.

Various articles evaluate the production of green hydrogen in different regions of the world. Gondal et. al assessed a green hydrogen potential using the full energy potential of biomass, solar, wind, and geothermal energy, among other energies in Pakistan using a conversion factor between electric power and hydrogen for its calculations [4]. Thapa et. al calculated the green hydrogen potential in Nepal with hydropower surplus using energy consumption per kilogram of hydrogen from an electrolyzer [5]. Posso et. al estimated the production of green hydrogen in Paraguay with a contribution of 93.34% of the solar energy coming from the west of the country, for the final uses of transportation and domestic use [6].

Similar to the previously mentioned studies, this research also evaluates the potential of hydrogen generation from renewable sources of a country, with the novelty that a Power-to-Power hydrogen plant was sized for each one of the twenty solar and wind power plants in Honduras that were studied in this research using a cost-benefit analysis as a decision criterion.

The rest of the document is structured as follows. “Methodology” explains the methodology followed in this work, “Results and discussion” shows the main results and its discussion, and “Conclusions” presents the main conclusions of this research

2 Methodology

The methodology in this research can be divided into the six following steps.

2.1 Sources and water consumption

Electrolyzers consume demineralized water during the electrolysis process. First, it is necessary to find a water source for each hydrogen plant and calculate the water consumption of the electrolyzer. Using [7] and its measure tool, the closest water source of each hydrogen plant was determined.

It is important to know that [8] cited in [9] mentions that in the demineralization process the loss of water resources is about 50%. Water consumption for one kilogram of hydrogen was determined by calculating the number of moles of water in one kilogram of water with the following equation:

$$Amount\ of\ substance = \frac{mass}{molar\ mass} \qquad (1)$$

Where mass is one kilogram of water and molar mass is the molar mass of water which is 0.01802 kg·(mol)-1. Once the number of moles of water in one kilogram of water is determined, the number of moles of hydrogen can be estimated with the following stoichiometric equation:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \qquad (2)$$

Equation (2) shows that for every mol of water there is one mole of hydrogen. The mass of hydrogen in one kilogram of water can be calculated by clearing mass from Equation (1). The water consumption depends on the electrolyzer and the type of water. The equivalence on the type of water used is shown in the following equation [10]:

$$1\ L\ \text{pure water} \rightarrow 1.43\ L\ \text{tap water} \rightarrow 3.33\ L\ \text{seawater} \qquad (3)$$

2.2 Cumulative energy generation curves

Different powers of electrolyzers multiples of the chosen electrolyzer power were analyzed. It was essential to calculate the amount of harnessed energy shedding for each power of electrolyzers to know how much green hydrogen each power can produce. For that, energy shedding, limited time and power data from [11] were processed. The data is from January 01, 2020, to June 30, 2022. It was necessary to create a code in Visual Basic Application that can sort the data on an hourly basis to create a cumulative energy generation curve.

Usually, in cumulative energy generation curves, the time is on the x-axis and the power is on the y-axis. Nevertheless, in this research, the axes were inverted to facilitate the calculation of the harnessed energy shedding by each power of electrolyzers as shown in Figure 1.

The harnessed energy shedding for each power of the electrolyzer was calculated by Riemann sum with rectangles of 0.1 MW of width to have a more detailed approximation. Since the data of limited power and time it is not that detailed, a polynomial regression was done in GNU Octave by choosing the degree of a polynomial whose curve most closely approximates the behavior of the original curve. An example is shown in Figure 2.

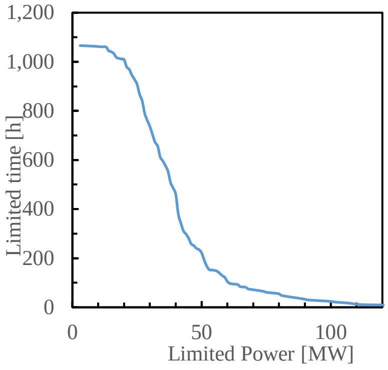

Fig 1. Example of cumulative energy generation curve (axes inverted).

Source: Own elaboration

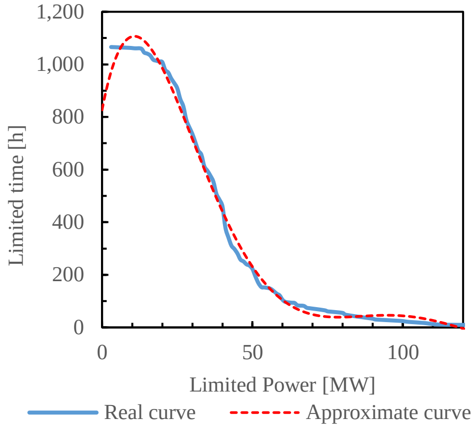

Fig 2. Example of approximate curve of polynomial regression.

Source: Own elaboration

In the polynomial regression an equation that can describe the curve was found with the following form:

$$y=a_0\cdot x^n\pm a_1\cdot x^{n-1}\pm a_2\cdot x^{n-2}\pm a_2\cdot x^{n-3}\pm a_2\cdot x^{n-4}\ldots\ a_n x+b \tag{4}$$

The harnessed energy shedding will increase as shown in Figure 3.

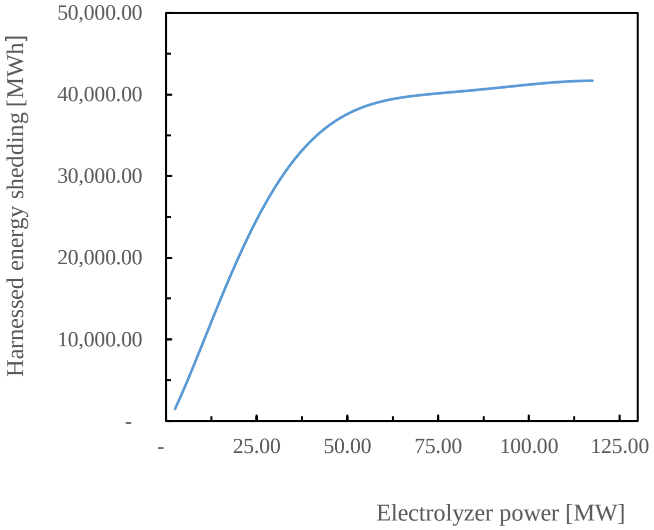

Fig 3. Example of harnessed energy shedding curve.

Source: Own elaboration

2.3 Hydrogen Power-to-Power plants sizing

Once the harnessed energy shedding by each power of electrolyzers is calculated, the hydrogen Power-to-Power plants can be sized. That means that all the different powers of electrolyzers are going to be sized by the following methodology:

- The water storage capacity is the water consumption of the electrolyzer in one day.
- The energy consumption of the electrolyzer it is found in the technical data of the chosen electrolyzer. This information is useful to estimate the amount of hydrogen produced annually in each plant. With the hydrogen produced in one year, an average of hydrogen production per day can be estimated to calculate the daily hydrogen storage capacity.
- The working time of the electrolyzer can be calculated by clearing t from the following equation:

$$m_{H_2s}=\int_0^t m_{H_2}\cdot dt \qquad (5)$$

Where m_{H_2s} is the daily hydrogen storage capacity, m_{H_2} is the electrolyzer hydrogen flow and t is the working time of the electrolyzer.

- And finally, the fuel cell is sized. For sizing the fuel cell, it is imperative to determine the working time. The fuel cell is going to work 12 hours, which is the night period where energy is going to be injected into the national electrical network.
- The power of the fuel cell can be estimated with the following equation:

$$P_{fc}=\frac{E_{daily}}{t} \qquad (6)$$

Where P_{fc} is the power of the fuel cell, E_{daily} is the energy that can be produced in one day from green hydrogen, and t is the working time of the fuel cell. E_{daily} can be calculated with the average hydrogen production per day from the electrolyzer and the hydrogen consumption from the fuel cell, found in the technical datasheet.

2.4 Cost-benefit analysis

A cost-benefit analysis is the decision criterion for choosing the sizing of the hydrogen plant of each solar and wind plant studied in this research. The cost-benefit analysis can be estimated with the following equation:

$$\text{Cost-benefit}=\frac{B}{C} \qquad (7)$$

Where B is the benefit from selling the energy at the same price that the contract of the existing renewable plant stipulates, and C is the cost, which includes the cost of investment of the hydrogen plant, operation and maintenance, water consumption, and electricity consumption from secondary equipment (hydraulic pump, compressor, and demineralizer).
The highest cost-benefit is identified in an optimization curve of the electrolyzer power as shown in Figure 4.

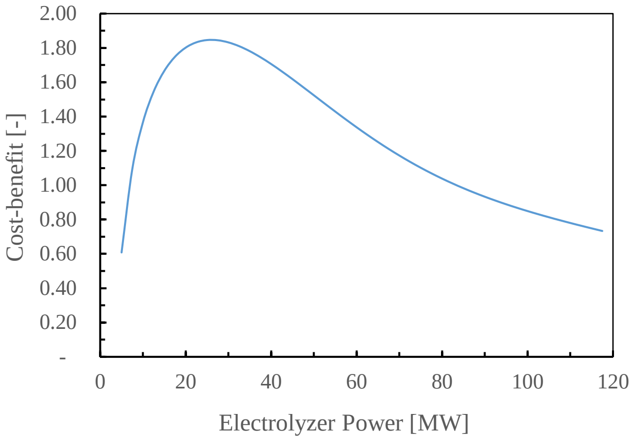

Fig 4. Example of electrolyzer power optimization curve.

Source: Own elaboration

2.5 Energy Return on Investment

The Energy Return on Investment (EROI) allows for analyzing the feasibility of green hydrogen production because it makes a comparison between the energy used during the process and the energy obtained at the end of the process. Figure 5 shows the energy used during the process (E_1, E_2, E_3, and E_4 which represents the energy consumed by the electrolyzer, hydraulic pump, demineralizer, and compressor, respectively) and the energy obtained at the end of the process (E_5 which represents the energy injected at the national electrical network in the night period).

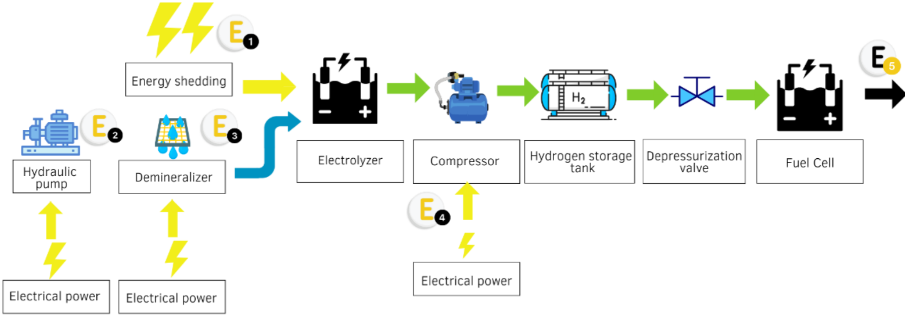

Fig 5. Power inputs and outputs in the system.

The EROI can be estimated by the following equation:

$$EROI=\frac{E_5}{E_1+E_2+E_3+E_4} \tag{8}$$

2.6 Carbon dioxide emissions mitigation potential

Energy generated with green hydrogen storage during the day, can be injected into the national electrical network in the night. Since the only by-product of the generation of green hydrogen is water, introducing the energy vector at the energy matrix can displace thermal energy generation during the night and reduce carbon dioxide emissions.
The annually carbon dioxide emissions mitigation potential can be calculated as:

$$Mitigation\ potential = E \cdot F_{cd} \tag{9}$$

Where E is the energy generated from green hydrogen per year and F_cd is the emission factor of fuel oil for energy generation. Which, according to [3] in 2020 contributed 33% to the energy generation as a primary energy source in thermal power plants. An emission factor of 0.6092 kg $CO_2 \cdot kWh^{-1}$ from [12] cited in [13] for fuel oil energy generation will be used.

3 Result and discussion

Water sources for every plant were determined. The results are shown in Table 1.

Table 1. Water sources results.

Plant	**Basin**	**Microbasin ID**
Cerro de hula	Nacaome	2204010
Cinco Estrellas	Sampile	2101027
Cohessa	Goascorán	2305006
Chincayote	Coco/Segovia	1801017
Choluteca dos	Sampile	2101021
Choluteca uno	Sampile	2101016
Enerbasa	Choluteca	1901008
Fray Lazaro	Choluteca	1901012
Nacaome dos	Goascorán	2305011
Nacaome uno	Goascorán	2305005
Fotersa	Sampile	2101019
Helios	Sampile	2101029
Lajas	Choluteca	1903043
Llanos del sur	Choluteca	1901012
Mecer	Sampile	2101029
Marcovia	Choluteca	1901024
Los pollitos	Chamelecon	405036
Prados sur	Sampile	2101043
San Marcos	Choluteca	1903038
Soposa	Goascorán	2305006

Source: Own elaboration with information from Agua de Honduras [7]

A Truper Expert one horsepower (1 hp) hydraulic pump was used for filling the water tank. This power was chosen because the time of filling must be equal to or under 12 hours (which is the night period).

The electrolyzer requires direct current to begin the electrolysis process, and a rectifier to convert alternate current (AC) to direct current (DC) is needed. To convert AC voltage from the renewable plants to DC voltage for the electrolyzer, a six-pulse diode bridge rectifier is used, which provides an average DC voltage according to the AC power supply voltage specification. Since the three-phase rectifier cannot be controlled with the use of diodes, a DC-DC buck converter must be use to control the current through the single power switch [14]. Figure 6 shows its operating diagram.

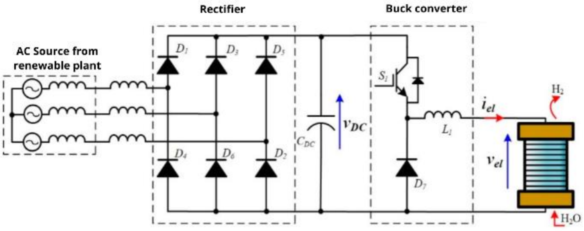

Fig 6. Six-pulse diode rectifier with converter operating diagram.

Source: Crozzoli et. al [14]

Theoretically, the water consumption for the electrolyzer is 25.56 kg of tap water for one kilogram of hydrogen produced. Since the water consumption also depends on the electrolyzer, the technical data of John Cockerill DQ 500 electrolyzer of 2.5 MW shows that it consumes 10.33 kg of demineralized water which equals 29.54 kg of tap water for one kilogram of hydrogen produced.

MAHYTEC hydrogen tanks were selected to store the hydrogen at 500 bar. High-pressure tanks can increase the energy density of the hydrogen. However, a compressor is essential since the output pressure of the electrolyzer is 30 bar. PDC-4 hydrogen compressors of 55 kW [14] were used to increase hydrogen pressure, this power was opted because its hydrogen flow matches the electrolyzer hydrogen flow. FCGen fuel cells of 5 kW from Ballard were selected because of its flexibility in cell arrangements to equal the sized fuel cell power for the hydrogen plants. Because the input pressure of the fuel cell is 5 bar, it was necessary to add a depressurization valve at the fuel cell input to lower the outlet pressure of the hydrogen tanks.

The input data for the plant sizing and cost-benefit analysis is shown in Table 2.

Table 2. Input data for plant sizing and cost-benefit analysis.

Inputs	**Value**	**Unit**	**Source**
Electrolyzer electricity consumption	0.04831	MWh· (kg H_2) $^{-1}$	Datasheet
Electrolyzer water consumption	29.54	kg H_2O· (kg H_2)$^{-1}$	Datasheet
Fuel cell hydrogen consumption	72.23	kg H_2 ·(MWh)$^{-1}$	Datasheet
Hydrogen tank capacity	9.5	kg H_2	Datasheet
Electrolyzer capital cost	1,000,000.00	\$·(MW)$^{-1}$	[15]
Fuel cell capital cost	3,000,000.00	\$·(MW)$^{-1}$	[15]
Hydrogen tank capital cost	455.00	\$· (kg H_2)$^{-1}$	[15]

Inputs	**Value**	**Unit**	**Source**
Water tank capital cost	0.038212	$\$\cdot (kg\ H_2O)^{-1}$	[14]
Compressor capital cost	2,500,000	$\$\cdot(MW)^{-1}$	[14]
Hydraulic pump capital cost	104.74	$	
O&M electrolyzer	2%	Capital cost	[16]
O&M fuel cell	2.5%	Capital cost	[16]
Water cost	0.00033	$\$\cdot (kg\ H_2O)^{-1}$	
Energy sell price	According to contract	$\$\cdot(MWh)^{-1}$	Decree no. 376-2013
Energy buy price	According to contract	$\$\cdot(MWh)^{-1}$	Decree no. 376-2013
Inflation	1.5%		Decree no. 404-2013
Compressor electricity consumption	0.00112	$MWh\cdot (kg\ H_2)^{-1}$	[14]
Demineralizer electricity consumption	0.000002	$MWh\cdot (kg\ H_2O)^{-1}$	[17]

With the input data, the sizing of sixteen hydrogen Power-to-Power plants was made, and the sizing with the highest cost-benefit ratio was selected. In total, 912 data points of energy shedding, limited power and time data were collected and processed into cumulative energy generation curves. For the analysis, the days in which there was no energy shedding were not considered. Only sixteen out of twenty plants were sized because during the elaboration of the cumulative energy generation curves, it was possible to identify that the plants: Fray Lazaro, Lajas, Los Pollitos, and Llanos del Sur did not have energy shedding, or more than 80% of the days of the sample they did not present energy shedding. Therefore, those plants were not sized.

Table 3 shows the result of the sizing for each plant, indicating the capacity of the components, the annual green hydrogen and electricity generation of each plant, and its cost-benefit.

Table 3. Sizing, generation, and cost-benefit results.

Plant	**Electrolyzer capacity [MW]**	**Storage capacity [kg H_2]**	**Fuel cell capacity [MW]**	**Green hydrogen generated per year [kg]**	**Electricity generated per year [MWh]**	**Cost-benefit [-]**
Cerro de hula	20	456	0.52	165,945.82	2,297.46	0.1540
Cinco Estrellas	7.5	228	0.26	81,480.93	1,128.08	0.2067
Cohessa	12.5	266	0.30	95,554.56	1,322.92	0.1696
Chinchayote	10	199.5	0.22	69,986.53	968.9	0.1380
Choluteca dos	7.5	180.5	0.21	65,180.21	902.39	0.1830
Choluteca uno	7.5	126.5	0.14	45,067.87	623.95	0.1457

Enerbasa	5	57	0.06	19,064.80	263.95	0.1055
Nacaome dos	10	228	0.26	80,817.92	1,118.89	0.1754
Nacaome uno	7.5	171	0.19	60,500.97	837.62	0.1752
Fotersa	5	38	0.10	31,196.22	431.90	0.1493
Helios	7.5	142.5	0.16	51,478.98	712.71	0.1587
Mecer	7.5	142.5	0.16	50,351.16	697.09	0.1565
Marcovia	10	228	0.26	82,909.43	1,147.85	0.1780
Prados sur	7.5	171	0.19	59,893.58	829.21	0.1741
San Marcos	10	180.5	0.21	66,219.88	916.79	0.1329
Soposa	10	275.5	0.25	79,620.06	1,102.31	0.1738
Total capacity	145	3,090.5	3.49	1,105,268.90	13,004.60	

Source: Own elaboration

The cost-benefit of every hydrogen plant is less than one, which means that the cost is greater than the benefit of the hydrogen Power-to-Power plants. A cost-benefit analysis for 2025 was made and the results are greater than the cost-benefit of 2022. Despite that, it is still less than one. The cost-benefit is affected by the working time of the plants (since they only work when there is energy shedding), the high cost of the plant, and the energy sales price assumed in the analysis (it can be assumed that in other countries the tariff for generating electricity at night and using hydrogen is higher).

Table 3 shows that Honduras can annually generate 1,105,268.90 kilograms of green hydrogen and 13,004.60 MWh of electrical energy from solar and wind energy shedding. Figure 7 shows the share of each hydrogen plants in Honduras per year.

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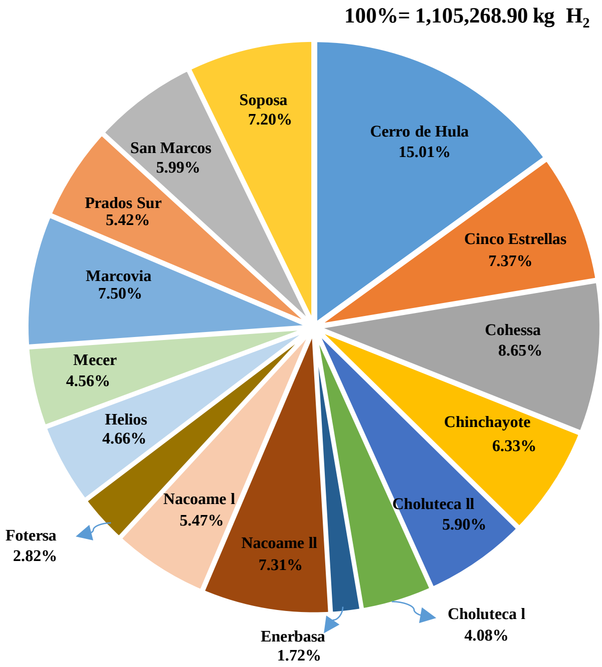

Fig 7. Share of each hydrogen plant in Honduras per year.

Source: Own elaboration

The efficiency of the plants is 28.66% which represents a low efficiency in all the processes. Nevertheless, this value is consistent with [18]. The low efficiency of the plants is due to the multiple energy conversion processes through which the energy is subjected to.

The Energy Return on Investment of the plants is 0.2797, which means that the energy input is highest than the energy output. This value is the same for the sixteen green hydrogen plants because the same model of electrolyzers and fuel cells were used in every sizing.

Because of green hydrogen generation, 13,004.60 MWh of electricity generated from fuel oil can no longer be generated. In this scenario, the carbon dioxide mitigation is 7,922,402.32 kg yearly.

4 Conclusions

A green hydrogen assessment of generation and storage potential from solar and wind energy shedding was made. The amount of green hydrogen, electrical energy generated and mitigation of carbon dioxide emissions per year was also determined. The analysis revealed the following results:

- Honduras can generate approximately 1,105,268.90 kilograms of hydrogen and 13,004 MWh of electrical energy in a year. Cerro de Hula is the biggest sharer with 15.01% of the green hydrogen and energy produced within a year followed by COHESSA with 8.65%.
- The cost-benefit of the hydrogen Power-to-Power plants is less than one, the highest is 0.2067 from Cinco Estrellas and the lowest is 0.1055 from Enerbasa which means that it is not economically feasible.

- The Energy Return on Investment is 0.2797, lower than one, which indicates that more energy is used in the Power-to-Power process than the energy obtained at the end of the process.
- In total, 7,922,402.32 kilograms of carbon dioxide per year can be avoided by implementing hydrogen plants that use energy shedding.

The main impediment of this research is the variability of power and time limitations of the renewable plants. Despite this impediment, it is believed that this research can serve as a guide for an estimation of green hydrogen potential in the different renewable plants. In this manner, hydrogen plants can be added in the future indicative plans for the expansion of electric power generation in Honduras. This would help in the process of the energy transition, decarbonization, frequency stability in the electrical power network, and independence from fossil fuels in the country.

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