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CONCEPTUAL ENGINEERING DESIGN OF THE GREEN HYDROGEN PRODUCTION PROCESS AS A MECHANISM TO CONTRIBUTE TO THE CARBON NEUTRALITY STRATEGY IN COLOMBIA

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ABSTRACT:
Due to the need to contribute to sustainable development, considering that one of its pillars is climate change mitigation, this study aimed to identify the technologies associated with green hydrogen production for their implementation in the energy transition. The goal was to develop a conceptual design including each of the unit operations required in the synthesis process. A water electrolysis system was designed, selecting the alkaline electrolyzer as the best option due to its maturity. A calculation basis of 20 kg of daily hydrogen production was used, estimating an electrical energy requirement of 9,170 kWh and a water flow rate of 300 L/day to feed the electrochemical unit. NaOH and/or KOH were chosen as electrolytes due to their potential to conduct electricity. To ensure green production, coupling with a photovoltaic system is proposed as a renewable electrical energy source. The required power to guarantee the electrolyzer's 24-hour/day operation was evaluated using the Photovoltaic Geographical Information System software, based on the reference value corresponding to the estimated generation capacity of the Solar Barranca project, located in the municipality of Barrancabermeja, Santander. To determine the electrolyzer's power, the hourly hydrogen production was calculated based on demand and operating time, yielding a result of 0.833 kg of H_2/h. Finally, the required power was determined to be 46.296 kW. Additionally, it can be concluded that by installing a capacity to store 20 kg of H_2 daily at 500 bar of pressure, an equilibrium pressure of 286 bar is reached, and 7.09 kg of H_2 would be released due to the pressure difference.

KEYWORDS: Green Hydrogen, Water Electrolysis, Photovoltaic System, Electric Energy, Carbon Neutrality

INTRODUCTION:

Energy consumption based on fossil fuels has been a key factor in climate change and public health problems due to pollution [1,2]. To address this problem, the transition to renewable sources is essential, highlighting green hydrogen as a key energy vector for decarbonisation and the reduction of GHG emissions [3,4]. In Colombia, its adoption is part of the carbon neutrality strategy by 2050, especially in industry and transport [5,6]. In this framework, the study proposes a conceptual model for the production of green hydrogen through electrolysis with photovoltaic energy, contributing to the country's energy transition.

Climate change has generated severe impacts on ecosystems and the quality of natural resources, aggravated by the use of fossil fuels [7,8]. According to the IPCC (2023) [9], the increase in global temperature is closely linked to the accumulation of GHGs, with the energy sector as one of the main emitters.

Decarbonisation is key in this context, and green hydrogen, obtained through electrolysis with renewable energy, is presented as a viable solution [10]. This study seeks to optimize their production to improve renewable energy storage, reduce GHG emissions, and facilitate energy access in non-interconnected areas [11,12]. In addition, it is expected to promote strategies in the scientific community for climate change adaptation and mitigation [13].

METHODS AND METHODOLOGY:

2.1 Description of green hydrogen production technologies in order to relate advantages and disadvantages
The methodology focused on the identification and characterization of technologies for the production of green hydrogen, analyzing their advantages and disadvantages based on their chromatic classification (green, blue, gray, pink and turquoise). A detailed diagnosis of the production techniques was made, identifying chemical and physical principles involved in these processes. Through a comparative analysis, technical, economic and environmental criteria were established to determine the most efficient and sustainable method, optimizing the performance in terms of flow, purity, storage and distribution of hydrogen.

The environmental impacts of green hydrogen production were evaluated using a matrix method that identified significant environmental aspects and their interaction with representative impact factors (FARI). The elements of the environment affected were determined, allowing to distinguish positive and negative impacts. In addition, a matrix was formulated that relates specific activities to the mitigated impacts, facilitating the identification of measures to minimize adverse effects and enhance environmental benefits. These findings are key to implementing clean technologies and strengthening sustainable strategies in the energy transition.

2.2 Determination of the feasibility of implementing water electrolysis technology to obtain hydrogen from the analysis of laboratory-scale studies
The study focused on electrolysis as a key method for the production of green hydrogen, evaluating its feasibility and integration with renewable energies. A scientific review of laboratory and industrial tests was carried out to understand the principles, operational variables and challenges of this technology. In addition, renewable energy sources (hydroelectric, solar, wind, biomass and geothermal) susceptible to electrolysis were identified, analyzing their viability based on availability of resources, government policies and socioeconomic conditions.

Likewise, the parameters required to guarantee sustainable production were defined, evaluating the quality of the water used and its impact on the process, as well as the energy needs to optimize the performance of the system. Water treatment alternatives and criteria were proposed to select the best energy solution, ensuring the efficiency and sustainability of green hydrogen within the framework of the energy transition and climate change mitigation.

2.3 Conceptual design of unit operations for the production of green hydrogen as an energy vector.
The conceptual design of the green hydrogen production system was based on theoretical models and numerical data, structuring a series of key steps. Electrolysis was identified as a central process for obtaining hydrogen, along with storage and distribution strategies. In addition, the optimal location of the plant was evaluated based on meteorological, geographical and economic conditions in Colombia, considering factors such as the availability of renewable energy and the existing infrastructure. To estimate the viability of the project, an analysis of the country's energy potential and the demand for hydrogen in productive sectors was carried out, taking Ecopetrol's pilot plant in Cartagena as a reference.

The sizing of the system included the selection of the type of electrolyzer and the calculation of the electrical and water requirements for the production of hydrogen. The electricity needed was calculated by the ratio presented in equation 1 and 2:

$$\text{Electricity}\left(\frac{\text{Nm}^3}{\text{day}}\right) = \text{Demand de H}_2\left(\frac{\text{kg}}{\text{day}}\right) X\ \frac{0{,}0899\ \text{Nm}^3}{\text{day}} \quad \text{Equation (1)}$$

$$\text{Electricity}\left(\frac{\text{kWh}}{\text{day}}\right) = \text{Electricity}\left(\frac{\text{Nm}^3}{\text{day}}\right) \text{X } 5{,}1\ \text{kWh/Nm}^3 \quad \text{Equation (2)}$$

For water consumption, the equation 3 was applied:

$$\text{Water flow(Q)} = \text{Demand de } H_2 \left(\frac{\text{kgH}_2}{\text{day}}\right) \text{X conversion factor} \qquad \text{Equation (3)}$$

The conversion factor is equivalent to the reason that 15 liters of raw (untreated) water are required to produce 1 kg of hydrogen through electrolysis [14].

A photovoltaic system was sized to supply production, through the use of the Photovoltaic Geographical Information System -PVGIS software to evaluate the solar potential. The power of the electrolyzer was determined with equation 4 and 5:

$$\text{Hourly hydrogen production}\left(\frac{\text{kg H}_2}{\text{h}}\right) = \frac{\text{Daily Hidrogen production }\left(\frac{\text{kg H}_2}{\text{day}}\right)}{\text{Hours of operation (24 h)}} \qquad \text{Equation (4)}$$

$$\text{Electrolyzer power (MW)} = \frac{\text{kg H}_2\text{ per hour}}{\text{conversion factor }\left(\frac{18\text{ kg/h}}{1\text{MW}}\right)} \qquad \text{Equation (5)}$$

Finally, low and high pressure storage strategies were designed, considering industry standards. For low pressure (35 bar), the number of tanks was estimated with equation 6:

$$\text{N° of tanks} = \text{Hydrogen produced}\left(\frac{\text{kg}}{\text{día}}\right) \text{X residence time days X } \frac{1\text{ tanque}}{620\text{ kg}} \quad \text{Equation (6)}$$

For high-pressure storage (500 bar), the volume of hydrogen was calculated with equation 7:

$$\text{Volume } H_2\ (\text{Nm}^3) = \text{Hydrógen produced (kg) X } \frac{1\text{ kg/day}}{0{,}0899\frac{\text{Nm}^3}{\text{day}}} \qquad \text{Equation (7)}$$

The pressure equilibrium was calculated using the ideal gas equation. The system ensures an efficient release of hydrogen and establishes a technical basis for its storage and distribution.

2.4 Analysis of the environmental component of the proposed system
In this fourth phase, the contributions of this study were identified and, specifically, the implementation of the design proposal, to the fulfillment of the objectives of sustainable development and under the scheme of the carbon neutrality strategy; taking into account the behavior of the interaction of the green hydrogen production project with the environment. Through the literature review, the carbon footprint was identified and analyzed, mainly in terms of avoided emissions compared to other ways of obtaining the energy vector.

RESULTS AND DISCUSSION

3.1 Description of green hydrogen production technologies in order to relate advantages and disadvantages
Table 1 presents the results obtained from the review of previous studies and analysis of scientific information for the survey of the bases that support the conceptual design generated.

The technical analysis of hydrogen production methods, presented in Table 1, allowed the identification of water electrolysis as the most viable technique due to its development, ease of operation and lower environmental impact. The technologies were classified into four main processes: thermochemical, photochemical, biochemical and electrochemical, highlighting the importance of continuing research in less common techniques. Although there are alternatives to water electrolysis that could be more efficient in production, their complexity makes their implementation difficult. Therefore, this study supports electrolysis as the best strategy for green hydrogen projects in planning in the country.

Table 1. Comprehensive analysis (vents and vents) between hydrogen production technologies

TECHNOLOGY	DESCRIPTION	ADVANTAGES	DISADVANTAGES
Biochemical [15]	Use of microorganisms to produce hydrogen.	Sustainable, low carbon emission, adaptable to different substrates.	Casualty efficiency production, limited competence of resources, processes in development.

Water electrolysis [16]	Decompositionn of the water with electricity	Compatible with renewable energies, production control, energy storage.	High costs, limited efficiency, energy storage. Demand for purified water.
Water electrolysis of hydrocarbons [17]	Use of natural gas and steam to extract hydrogen.	Loud efficiency integration with the industry existent Stable supply.	Emission of CO_2, dependence of fuels Fossils need for carbon capture.
Photochemistry [15]	Use of sunlight to activate reactions that release hydrogen.	Fountain renewable with emissions, potential for high efficiency.	Casualty conversion of energy solar dependence of catalytic converters, operation limited to daylight hours.
Hydrugification [15]	Reaction of biomass or hydrocarbons with high temperature vapor	Use of materials varied, use of waste	Emission of gases Pollutants costs Energy High technical complexity.
Laser pulses [15]	Use of lasers to activate chemical reactions.	Loud selectivity efficiency energetics reduction of Catalysts.	Expensive equipment, high energy consumption, difficult scalability.
Electrodecomposition with plasma [16]	Use of plasma to decompose materials into hydrogen.	High purity, energy efficiency, reaction control.	Costs High loud demand of energy technical barriers to its scaling.

Table 2 presents the interaction of the ASPI with the FARI that were identified, where the direct environmental impacts on the environmental component of projects are deduced; which could adopt hydrogen as an energy vector for the supply of electricity in the operation of equipment and infrastructure in general.

Table 2. Interaction between ASPI and FARI for the determination of possible environmental impacts that are configured.

MEDIUM	ENVIRONMENTAL COMPONENT	ASPI	FARI
Abiotic	Water	Land clearing, excavations	Quantity and quality of water
		Production or operational processes	Quantity and quality of water
		Storage of fuels, raw materials, and supplies	Water quality
		Operation of camps and restaurants	Quantity and quality of water
		Road maintenance	Quantity of water
		Drilling of wells for hydrocarbon exploration or exploitation	Quantity and quality of water
	Soil	Land clearing, excavations	Land use
		Operation of machinery and equipment	Compaction, erosion
		Vehicle operation	Compaction, erosion
		Production or operational processes	Land use
		Storage of fuels, raw materials, and supplies	Land use
		Road maintenance	Compaction, erosion
		Drilling of wells for hydrocarbon exploration or exploitation	Soil composition and use, erosion
	Air	Land clearing, excavations	Particulate matter
		Operation of machinery and equipment	Noise level, air quality
		Vehicle operation	Air quality

		Production or operational processes	Air quality, odor level, noise level
		Storage of fuels, raw materials, and supplies	Offensive odor level
		Road maintenance	Air quality
		Drilling of wells for hydrocarbon exploration or exploitation	Air quality, sound pressure level
	Landscape	Land clearing, excavations	Visual quality
		Storage of fuels, raw materials, and supplies	Visual quality
		Road maintenance	Visual quality
		Drilling of wells for hydrocarbon exploration or exploitation	Visual quality
	Climate	Land clearing, excavations	Wind, temperature
		Operation of machinery and equipment	Temperature
		Vehicle operation	Temperature
		Production or operational processes	Wind, temperature
		Operation of camps and restaurants	Temperature
		Drilling of wells for hydrocarbon exploration or exploitation	Temperature
Biotic	**Terrestrial Vegetation**	Land clearing, excavations	Diversity, abundance, structure
		Production or operational processes	Diversity, abundance, structure
		Drilling of wells for hydrocarbon exploration or exploitation	Diversity, abundance, structure
	Terrestrial Fauna	Land clearing, excavations	Diversity, abundance
		Production or operational processes	Diversity, abundance
		Drilling of wells for hydrocarbon exploration or exploitation	Diversity, abundance
Anthropic	**Economic**	Land clearing, excavations	Income level
		Operation of machinery and equipment	Income level
		Vehicle operation	Income level
		Production or operational processes	Income level
		Operation of camps and restaurants	Income level
		Road maintenance	Income level
		Drilling of wells for hydrocarbon exploration or exploitation	Income level
	Demographic	Land clearing, excavations	Employment level. Quality of life
		Operation of machinery and equipment	Employment level. Quality of life
		Vehicle operation	Employment level. Quality of life
		Production or operational processes	Employment level. Quality of life
		Operation of camps and restaurants	Employment level. Quality of life
		Road maintenance	Employment level. Quality of life
		Drilling of wells for hydrocarbon exploration or exploitation	Employment level. Quality of life

The implementation of a green hydrogen production plant through water electrolysis, coupled with photovoltaic energy, contributes significantly to the reduction of environmental impacts, especially on air and water quality. In terms of air pollution, this technology reduces the emission of gases and particulate matter by replacing conventional sources of energy, generating an estimated carbon footprint of between 1.3 and 2.5 kg CO_2/kgH_2, one of the lowest compared to other technologies [16].

In addition, the combustion of hydrogen only produces water vapor, avoiding criteria pollutants present in fossil fuels. Regarding water, the use of wastewater treated in the electrolyzer prevents contamination and allows its reuse without affecting the quality of the natural resource. Likewise, this strategy avoids the extraction of water from natural sources, guaranteeing its availability for essential uses such as human consumption and the protection of aquatic ecosystems, in accordance with Decree 1076 of 2015. Finally, the reduction of GHG emissions through this technology contributes to mitigating climate change, aligning with the carbon neutrality strategy and the sustainable development goals.

3.2 Determination of the feasibility of implementing water electrolysis technology to obtain hydrogen from the analysis of laboratory-scale studies

Studies on electrolysis for hydrogen production have explored various sources of renewable energy. Bedoya & Medina (2021) concluded that wind energy is the most appropriate due to its greater generation capacity compared to solar, highlighting La Guajira as an ideal site due to its wind conditions and access to seawater [13]. Tisza et al. (2022) optimized the process using electrical circuits, demonstrating that connecting electrolysis cells in series increases production [18]. Rojas & Quilaguy (2023) experimentally validated Faraday's laws in an alkaline electrolyser, highlighting the importance of airtightness in its operation [19]. Herdoiza (2022) recommended the use of PEM-type electrolyzers due to their ease of construction and efficiency [17], while Vermeersch (2018) evidenced the low efficiency of electrolysis at low pressure and without additives in the electrolyte [20].

The most viable renewable energies for green hydrogen production include solar, wind, and hydropower. Solar energy, through thermal and photovoltaic systems, allows for carbon-free production [21]. Wind energy converts the kinetic energy of the wind into electricity through wind turbines, ensuring a sustainable supply [22]. On the other hand, hydroelectric transforms the energy of moving water into electricity, using turbines and generators [23]. Integrating an electrolysis system with a renewable source is feasible, although it requires a significant initial investment, offset by long-term environmental and economic benefits. In addition, parameters such as energy storage, climatic factors and chemical composition of water must be considered to optimize hydrogen production.

3.3 Conceptual design of unit operations for the production of green hydrogen as an energy vector.

3.3.1 Criteria for Plant Location

- Important Factors

1. Availability of Renewable Energy: Selection of areas with high solar irradiation and analysis of meteorological data has a crucial role in the operation of the system.
2. Hydrogen Demand: Identification of the industrial sectors that consume hydrogen, including metallurgy and petrochemicals, allows the plant to be sized appropriately.
3. Hydrocarbon Infrastructure: Taking advantage of the existing infrastructure in the hydrocarbon sector for the transport of hydrogen can optimize resources.
4. Available Water Resources: Assessing the supply of water, including the use of wastewater, is essential for hydrogen production

- Identification of areas in Colombia with potential for clean energy generation that are projected for availability of hydrogen plant supply sources

La Guajira, Atlántico and Magdalena are identified as the best regions for the implementation of these projects, thanks to their high solar radiation and favorable winds [24].

3.3.2 System Sizing

- Calculated Demands

It is estimated that the plant should produce 20 kg of H_2 per day, which is equivalent to an electrical need of 9,170 kWh/day:

$$\text{Electricity}\left(\frac{\text{Nm}^3}{\text{day}}\right) = 20\left(\frac{\text{kg}}{\text{day}}\right) \text{X} \frac{0{,}0899\text{Nm}^3/\text{day}}{1\ \text{kg/day}} = 1{,}798\ \text{Nm}^3/\text{day}$$

$$\text{Electricity}\left(\frac{\text{kWh}}{\text{día}}\right) = 1{,}798\left(\frac{\text{Nm}^3}{\text{día}}\right) \text{X} \frac{5{,}1\ \text{kWh}}{\text{Nm}^3} = 9{,}170\ \text{kWh/day}$$

- Electrolysis and Electrolysers

An alkaline electrolyser is chosen due to its technological maturity. The power required for the electrolyzer is 46,296 kW, calculated as:

$$\text{Hourly hydrogen production}\left(\frac{\text{kg H}_2}{\text{h}}\right) = \frac{20\left(\frac{\text{kg H}_2}{\text{día}}\right)}{24\ \text{h}} = 0{,}833\ \text{kgH}_2/\text{h}$$

$$\text{Electrolyzer power (MW)} = \frac{0{,}833\ \text{kg H}_2/\text{h}}{\frac{18\ \text{kg/h}}{1\text{MW}}} = \mathbf{0{,}046\ MW = 46{,}296\ kW}$$

➢ Water Calculations
The water flow required for production is 300 liters/day, destined for the electrolyzer:

$$\text{water flow rate (Q)} = 20\left(\frac{\text{kgH}_2}{\text{day}}\right) \text{X}\ 15\,\frac{\text{L}}{\text{kg}} = \mathbf{300\ L\,\frac{H_2O}{day}}$$

➢ **Sizing of the required area for the installation of the green hydrogen pilot plant**

$$\text{Plant area }(\text{m}^2) = 0{,}220(\text{MWp})\text{X}\left(\frac{3\ \text{ha}}{\text{MWp}}\right)\text{X}\ \frac{10.000\ \text{m}^2}{\text{ha}} = \mathbf{6600m^2}$$

Annual Energy Analysis The energy production of the plant must cover the demand of the hydrogen production system, with a minimum percentage of 0.2% of its total capacity to ensure sufficient energy for the operation of the electrolyzer.

3.4 Analysis of the environmental component of the proposed system

The transition to green hydrogen will mitigate polluting gas emissions and contribute to the Sustainable Development Goals (SDGs). Inclusions in the SDGs related to clean energy, decent work and economic growth, and climate action are projected [25].

It offers important environmental benefits, mainly the reduction of polluting gas emissions, replacing the burning of fossil fuels with a process that generates water as a by-product. In addition, the use of wastewater to feed electrolyzers is proposed, reducing the impact on natural water resources.

This approach contributes to the UN's Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy) by integrating renewable sources such as photovoltaic energy. It also promotes SDG 8 (Decent Work and Economic Growth) by creating job opportunities and boosting the economy around this new source of energy. Likewise, SDGs 9, 11, 12, 13, 14 and 15 related to innovation, sustainable infrastructure, responsible consumption, climate action and ecosystem protection are promoted.

CONCLUSIONS

The study highlights progress in the production of hydrogen as an energy vector, especially green hydrogen, which, by using renewable sources, minimises the carbon footprint and pollutant emissions. Water electrolysis is identified as the most developed and profitable technique to obtain hydrogen, requiring water and electricity supply, which could come from wastewater, thus complementing sustainability in the decarbonisation of the productive sector.

Mathematical models are adopted for the design of green hydrogen production systems, choosing the alkaline electrolyzer as the best option, with calculation bases that allow the system to be sized and key variables such as energy, water consumption and power to be estimated. The study addresses the challenge of hydrogen storage and distribution, sizing storage units at low and high pressure, and defining criteria for the location of the plant considering these needs.

The production of green hydrogen is aligned with several Sustainable Development Goals, contributing to the reduction of GHG emissions and avoiding negative environmental impacts. The technical sheet serves as a fundamental scientific resource for future research or planning of investment projects in the electrolysis of water and hydrogen production.

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