The viability and energy management for green hydrogen production from industrial wastewater treatment

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Abstract— **Amid global decarbonization efforts, transitioning from coal faces challenges despite its urgency. Green hydrogen emerges as a promising alternative amid natural gas market fluctuations. This thesis explores green hydrogen integration in wastewater plants, optimizing existing infrastructure. Assessing technical and economic benefits, it leverages renewables and boosts industry revenue. The study emphasizes synchronized energy consumption for efficiency and highlights advanced energy management and circular economy practices. Aligning with sustainability standards, industries can contribute to a cleaner, resilient energy future.**

Keywords: Green hydrogen, Electrolysis, Energy management, Renewable energy, Energy markets, Energy consumption

I. INTRODUCTION

As global efforts intensify towards achieving a decarbonized society or a 'Net-Zero' state, the phase-out of coal from the energy matrix, outlined in the IEA Net-Zero scenario for 2050, is deemed a prerequisite. Despite this widely acknowledged goal, COP26 underscored the challenges associated with securing commitments from major economies. While the economic and political motivations drive the stances of China and the US, India and other nations are influenced by the economic reliance on coal in specific regions, where coal contributes significantly to the GDP and plays a pivotal role in combating high levels of poverty.

Hydrogen is poised to play a critical role in the global economy's decarbonization, with various agencies, including the International Energy Agency, projecting substantial hydrogen utilization by 2030 and 2050, aimed at achieving Net-Zero carbon emissions in Europe. Recent years have witnessed significant turbulence in the natural gas market due to geopolitical tensions, supply chain disruptions, and climate change concerns, leading to price spikes and volatility. The conflict in Ukraine, tensions with Russia, and disruptions in natural gas supply to Europe have accentuated the urgency for sustainable and reliable energy alternatives.

Amid these challenges, the significance of a sustainable and dependable energy source has gained prominence. Green hydrogen, derived from electrolysis using renewable energy sources like wind and solar power, has emerged as a promising substitute for natural gas. The European Union's unveiling of a hydrogen strategy, aimed at ramping up green hydrogen production and usage, aligns with its target of achieving carbon neutrality by 2050. Additionally, the EU has introduced legislative packages, including the European Green Deal, focusing on the promotion of renewable energy adoption, improved energy efficiency, and the development of clean technologies such as green hydrogen.

However, scaling up hydrogen production presents significant challenges. Given that most of the world's hydrogen isn't commercially produced and sold but rather generated for specific on-site purposes, accounting for hydrogen production poses unique difficulties. The transition towards a more sustainable energy future necessitates a substantial shift in energy production and consumption practices. Green hydrogen, while a promising alternative to fossil fuels, demands considerable energy and water resources, thereby incurring potential costs and environmental impacts.

In this context, industries with wastewater treatment plants offer a distinctive opportunity for integrating green hydrogen production into existing infrastructure. Leveraging treated water available in the electrolysis process or through planned water treatment initiatives, these industries can not only curtail their carbon footprint but also realize economic and technical advantages. This thesis endeavors to explore the feasibility and energy management of green hydrogen production from industrial wastewater treatment plants. Focusing on an energy management system that optimizes hydrogen integration, the model aims to strike a balance in energy demands, maximize renewable energy utilization, and quantify the technical and economic benefits of green hydrogen production.

By focusing on the integration of green hydrogen production in wastewater treatment plants, the thesis seeks to present a practical demonstration of the technical and economic viability of such initiatives. The integration of green hydrogen production has the potential to serve as a renewable energy source, reducing the overall carbon footprint of industrial operations. Moreover, it can create an additional revenue stream by facilitating the sale of excess hydrogen in the market. Given the opportune timing for the development of green hydrogen, this thesis aims to contribute to the industry's growth by providing a viable solution for the optimized integration of hydrogen production in industries with wastewater treatment plants.

II. HYDROGEN'S ROLE IN THE NET ZERO EMISSIONS SCENARIO

The European Green Deal, introduced in 2019 by the European Commission (EC), aims to achieve net-zero greenhouse gas (GHG) emissions by 2050, necessitating a reduction of at least 55% by 2030 compared to 1990 levels (1). The increasing share of hydrogen in the total final energy consumption is projected to reach 2% by 2030 and 10% by 2050, highlighting its growing significance in the global energy landscape (2). The Net Zero Emissions scenario foresees a total hydrogen production exceeding 500Mt by 2050, primarily through electrolysis-based and blue hydrogen methods (3). Policies that incentivize the investigation and application of hydrogen as a source of energy in Europe and Portugal

In a general context, numerous policies incentivize the development of hydrogen, such as the recovery and resilience plan (PRR) for Portugal, innovation calls from the Portuguese agency of innovation, and the roadmap for carbon neutrality 2050, among others. This section focuses on the National Energy and Climate Plan 2030 and the National Hydrogen Strategy (EN H2).

A. *The strategy in the EU*

In July 2020, the European Commission (EC) released its hydrogen strategy to achieve the goals for the European Green Deal, focusing on renewable hydrogen. The targets presented in the strategy are broken down into three phases; Today-2024, 2025-2030 and 2030 onwards.

Until 2024, at least 6GW of renewable hydrogen electrolysers will be installed in the EU, a number that will increase to 40GW by 2030, producing up to 1Mt and 10Mt of renewable hydrogen by 2024 and 2030, respectively (1). The Fit For 55 legislative package was presented by the EC in mid-2021, including 5.6Mt of hydrogen from renewable sources, with a heavy emphasis on the production of green hydrogen.

This path has seen changes, with the EU presenting increased targets in the face of the war in Ukraine. The REPowerEU plan outlines the EU's path to energy independence from Russian fossil fuels by 2027, with an increase in hydrogen goals from 5.6Mt to 20Mt by 2030, aiming to replace 25 to 50 billion cubic meters of Russian gas. In addition, 120GW of electrolysers are to be installed by 2030, alongside the previously planned 40GW, to aid in domestic hydrogen production.

Under REPowerEU, domestic production and imports of hydrogen in the form of ammonia and other derivatives are projected to play a significant role, unlike in the initial plan. Other sectors expected to have substantial increases in hydrogen usage include industrial heat, petrochemicals, refineries, and transportation.

B. *National Energy and Climate Plan 2030 towards a carbon-neutral future (PNEC 2030)*

The National Energy and Climate Plan 2030 (PNEC 2030), published in 2019, was developed to comply with the obligations assumed by member states under the EU Regulation 2018/1999 on the Governance of the Energy Union and climate action. It serves as the primary instrument of Portugal's energy and climate policy for 2021-2030, guiding the country toward decarbonization of the economy.

C. *The National Hydrogen Strategy (EN H2))*

The National Hydrogen Strategy (EN H2) was approved by the Council of Ministers in May 2020 and made available for public consultation until July 2020. The strategy aims to incorporate hydrogen into various segments of the Portuguese economy, particularly focusing on green hydrogen produced exclusively from processes using renewable energies. The strategy provides a framework for private sector hydrogen projects and promotes an industrial policy around hydrogen, outlining policies to guide, coordinate, and mobilize public and private investments in hydrogen-related projects in Portugal.

D. *Principle of Additionality in Relation to Renewable Hydrogen*

The principle of additionality is crucial in evaluating the feasibility of green hydrogen production. It ensures that the claimed emission reductions or energy production are genuine and not already accounted for in other initiatives or actions. The application of the principle of additionality helps maintain the integrity of environmental claims and prevents the inflation of benefits, providing an accurate assessment of the actual impact of green hydrogen production.

III. GREEN HYDROGEN PRODUCTION, ADVANTAGES, AND DISADVANTAGES

Green hydrogen is obtained using renewable energies in its production, which makes it a clean, sustainable fuel with a zero-pollution index that can be key not only as an energy vector, but also as a raw material.

The great value of green hydrogen in the fight against climate change lies in its ability to replace fossil fuels in those sectors and uses that until now were more difficult to decarbonize, in addition to its potential as an energy storage system.

A. *Gree What is Green Hydrogen and How is it Obtained?*

Green hydrogen is produced through an electrolysis process powered by renewable energies such as wind or solar. Electrolysis involves using an electric current to break down water molecules into oxygen and hydrogen through electrodes. This eco-friendly method replaces additives in the water, making the process more sustainable (2). Access to clean water is crucial for production, and a certain level of salt can be used to increase conductivity. Several promising technologies like Alkaline Water Electrolysis, PEM, and AEM are being explored for efficient and cost-effective green hydrogen production (4).

B. How does Green Hydrogen Distribute?

Distribution of green hydrogen occurs through pipelines, high-pressure tubular trailers, liquefied hydrogen tanks, and ammonia as a hydrogen carrier. Blending hydrogen with natural gas in pipelines allows for gradual integration without extensive modifications. Decentralized production offers advantages by reducing long-distance transportation costs, promoting energy independence, and fostering local economic growth (5).

C. Uses and Advantages of Green Hydrogen within the Economy

Green hydrogen finds use in various sectors such as transportation, electricity and thermal energy storage, industrial processes, metal refining, and the production of fertilizers and chemicals. Its versatility and sustainable nature make it a valuable resource for decarbonizing hard-to-abate sectors such as maritime and air transport. Green hydrogen also presents an opportunity for countries like Portugal to establish an export market, contributing to regional economic growth (6)

D. Drawbacks of Green Hydrogen

While green hydrogen offers numerous advantages, it also faces challenges. These include its higher cost of production due to the expensive nature of renewable energy sources, greater energy requirements compared to other fuels, safety concerns due to its volatility and flammability, and potential leakage issues due to the molecular properties of hydrogen. Despite its drawbacks, the decreasing cost of renewable energy sources is making green hydrogen production more competitive in the market (7).

IV. WATER AND THE CHALLENGES FOR GREEN HYDROGEN

The principal constraints for scale production of green hydrogen before the commercial aspect of green hydrogen is advanced; the costs of renewable energies need to be viable themselves, the storage of electricity generated is still too inefficient, the storage of hydrogen too volatile, the costs of desalination remain significant and important, there is a lack of industrial demand for hydrogen. Assuming that all these barriers are knocked, there are still a big aspects to keep in mind.

A. Water Demand

For this exercise, the total future need for hydrogen in all applicable sectors, including chemical synthesis, transportation, buildings and heating, and energy storage, is considered. The calculated hydrogen demand in the distant renewable future is 2.3 Gt per year. For the purpose of this work, hydrogen will be produced by water electrolysis powered by renewable energy. (8) "With a projected need of 2.3 Gt H2 annually, it can decarbonize around 18% of energy-related sectors. In the long term, hydrogen can complement renewable electricity and be the keystone to a 100% renewable future." (9) In this sense, we can reduce carbon emissions from the energy sector by up to 10 Gt. It is essential to determine the feasibility of the amount of water 2.3 Gt of hydrogen will require each year. This is a concern for the conservation community, stating that obtaining water for the economy will be too expensive or demanding on the water and energy requirements. Based on the relationship: 1 kg of hydrogen produced = 9 kg of water consumed (Herib Blanco, 2021) For 2.3 Gt of hydrogen, 20.5 Gt, or 20.5 billion m3/year of freshwater will be needed. If we assume that this water won't return to the original source, we can assume that this amount of water is consumed. This assumption can be made because we use renewable energy to produce hydrogen, which consumes little water for its production. When fossil fuels are used for primary energy production and power generation, the water requirement is quite significant. In 2014, 251 billion m3 of freshwater was withdrawn for power generation and energy production from fossil fuels such as coal, oil, and natural gas, and 31 billion m3 were consumed as the water was used for cooling, mining, hydraulic fracturing, and refining (11). In comparison, the 20.5 billion m3/year is still 33% less water. According to the UN: "When a territory withdraws 25 per cent or more of its renewable freshwater resources, it is said to be 'water-stressed'." Globally in 2018, just 18.4 percent of total renewable freshwater resources were being withdrawn. Regionally, though, there are already places experiencing serious issues. Northern Africa has critical water stress levels, while Central and Southern Asia were classed as having high water stress. On the other end of the scale, 31 percent of the global population remained at the “no stress” level.

B. Water Quality Requirements for Water Electrolysis

According to what (12) describes as essential to start talking about the water needed for hydrogen production, first, it has to be mentioned that three kinds of water will be needed for the whole process: • Ultrapure water (for the electrolyser) • Cooling water • Raw water Ultrapure water Electrolysis requires ultrapure water with low conductivity levels to avoid impurities that can damage or reduce the efficiency of electrolysis systems. Factors like electrode material, system design, and water impurities all affect water quality requirements, making it difficult to establish a unified standard. To simplify the issue, manufacturers can set low conductivity requirements, such as <1 µS/cm for standard alkaline electrolysers and <0.1 µS/cm for advanced electrode alkaline and PEM electrolysers. While water treatment is a minor expense in hydrogen plants, ensuring reliable water treatment is crucial for successful electrolysis. According to the data (12), conductivity levels should be <1 µS/cm for standard alkaline electrolysers and <0.1 µS/cm for advanced electrode alkaline and PEM electrolysers. It is worth noting that water treatment is a small part of the total CAPEX of a hydrogen plant. With oxygen being 16 times heavier than hydrogen, it accounts for 89% of water's total mass. Therefore, to generate 1 kg of hydrogen, 9 kg of water are required

Cooling water The consumption of cooling water is more difficult to evaluate due to the variety of cooling solutions available, ranging from dry cooling to seawater cooling. The specific design of the cooling solution determines the amount of water used, with factors such as water quality and cooling method affecting consumption. However, as a rule of thumb, 400 L/h of cooling water is required per MW of electrolyser capacity for water-based cooling systems, which is roughly twice the amount required for electrolysis. It is important to note that water for cooling and electrolysis has different quality requirements. (12)

Raw Water Raw water would be the original source from where we will obtain the ultrapure water, this raw water can be obtained from different sources, depending on the size of the project the raw water can be drinking water. However, with the constant increase in size of green hydrogen projects, this approach becomes more unsustainable. For large-scale projects, other sources are considered as viable, such as groundwater, treated wastewater, and seawater. In the next figure, it can be appreciated that depending on the source, raw water will require different water treatment (In typical conditions). The water requirements for a green hydrogen project depend on the raw water source and the desired level of purity. Groundwater can achieve high recovery values of over 98%, while treated wastewater with ultrafiltration typically has a slightly lower recovery of 90-95%. Seawater desalination has a limited recovery of 40-50% due to osmotic pressure. The treatment process itself has a recovery rate of around 75% for ultrapure water. (12)

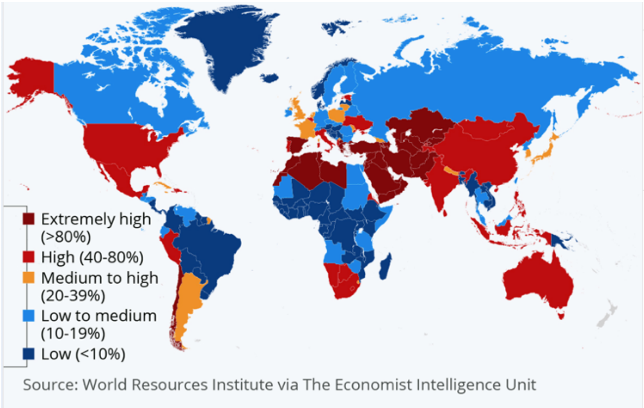
C. Water Demand

While the transition to green hydrogen production has been hailed as a potential solution to reduce carbon emissions and dependence on fossil fuels, it's crucial to assess the water demands associated with this shift. The process of electrolysis, integral to green hydrogen production, involves considerable water consumption. Several factors influence the water usage, such as the type of electrolyzer, the conditions of the electrolysis process, and the quality of hydrogen produced. According to the National Renewable Energy Laboratory, the water consumption for green hydrogen production varies between 9 and 12 liters per kilogram of hydrogen, depending on the electrolyzer's efficiency.

D. Water Supply and Water Stress

Despite the potential benefits of green hydrogen, the growing water demand raises concerns, particularly in regions already facing water stress. The UN's definition of 'water-stress'—when a territory withdraws 25% or more of its renewable freshwater resources—reveals a precarious situation in several parts of the world. Notably, Northern Africa experiences critical water stress levels, while Central and Southern Asia face significant water stress challenges. Projections from the World Resources Institute for 2040 suggest that the issue will exacerbate due to urbanization, population growth, climate change, and economic development (13).

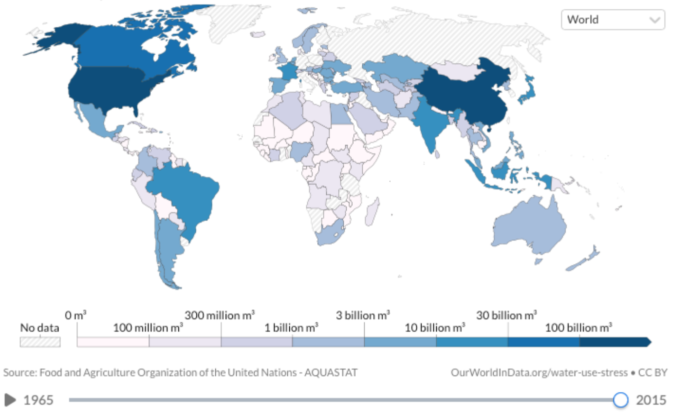
Figure 1 illustrates the projected areas of high water stress by 2040, emphasizing the pressing need to address water availability and consumption. Additionally, historical trends, as depicted in Figure 9, show a significant increase in global freshwater consumption over the past 50 years, further highlighting the urgency of sustainable water management.



Source: World Resources Institute via The Economist Intelligence Unit

Figure 1. Where water stress will be highest by 2040
Source: *World resources institute – The economist intelligence unit / Statista*

The role of the industrial sector in limiting water pollution and stress is emphasized in UNESCO's World Water Development Report 2022. Water usage in industries such as steam generation, equipment washing, and cooling processes is substantial, with the United States alone consuming over 300 billion cubic meters of industrial water annually, as shown in Figure 2 (13).



Source: Food and Agriculture Organization of the United Nations - AQUASTAT
OurWorldInData.org/water-use-stress • CC BY

Figure 2. Industrial water withdrawal 2015
Source*:* Food and Agriculture Organization of the United Nations – AQUASTAT

E. Desalination of Saltwater

While green hydrogen production can significantly impact water resources, incorporating desalination into the process can mitigate potential strain on freshwater supplies. Although the desalination process adds to the energy requirements of hydrogen production, it becomes a viable option when considering the abundance of saltwater resources. The use of reverse osmosis, a common desalination process, necessitates 3.5–5 kWh of energy per cubic meter of clean water produced

(12). Despite the energy requirements, the advantage lies in the availability of saltwater resources and the potential for recycled water usage in arid regions.

Considering the projected global hydrogen demand of 2.3 Gt, the additional energy required for reverse osmosis in water electrolysis would range between 0.26 and 0.37 EJ annually. Given that the energy source is renewable and the marginal price is zero, this additional energy demand remains manageable.

Figures 3 provide a comparative analysis of global freshwater consumption by different sectors, illustrating the substantial water demands from various economic and social applications. While the water requirements for green hydrogen production are notable, the implementation of sustainable practices, including water reuse in industrial processes, can help mitigate potential adverse impacts on local water supplies.

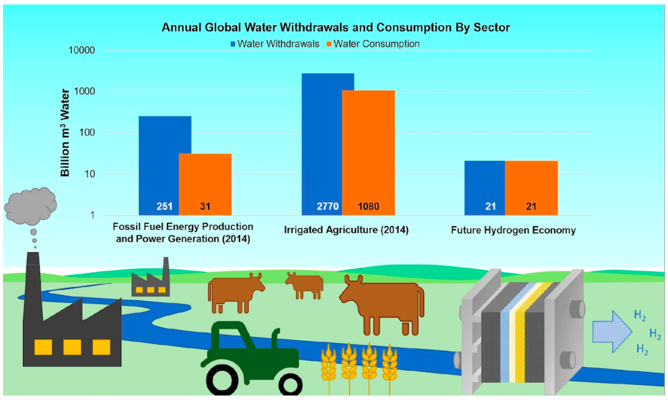


Figure. 3. Annual global water withdrawals and consumption by sector
Source: *ACS Energy Lett. 2021)*

V. WASTEWATER TREATMENT PROCESSES AND ITS POTENTIAL FOR HYDROGEN PRODUCTION.

As mentioned above, industrial water use can be significant, highlighting the need to adopt circular economy principles when dealing with wastewater treatment plants.

Within the wastewater treatment process, the amount and nature of by-products or waste generated will vary depending on factors such as the complexity of the process, the type of industry, and the purpose of treatment (e.g., water reuse, human consumption, cooling systems, etc.). For the purposes of this study, it is assumed that the water will be used in the production of green hydrogen, which requires the highest possible level of purity.

Following what Jing et al. Argues the reasons why producing green hydrogen from waste water treatment water is a good idea are:
(13)

- The use of fresh water to produce green fuel can exacerbate the challenges of water scarcity, especially in countries located in the Middle East.
- Using other available resources as a feedstock of the electrolysis process can ensure the sustainability and security of fuel production by balancing the availability of water and hydrogen fuel production.
- In their publication Jing et al. proposed hydrogen production process utilizes purified wastewater and waste heat of flue gases of the power plants as feedstocks for the water electrolysis process. ‘’it is possible to use waste heat of power plant flue gases and wastewater as feedstocks for such electrolyzer stacks. Reasonable use of waste heat and thermal optimization can be the key point to achieve a sustainable hydrogen production process. Therefore, the development of such green hydrogen fuel production processes based on the waste heat of power plants and urban wastewaters can be a synergistic point toward the sustainable development of cities (14)(13)
- Exploitation of the proposed hydrogen production process, in addition to reducing energy consumption, can mitigate greenhouse gas emissions.
- Acid and base are recovered for the wastewater treatment process, which can provide additional benefits.

The circular processes involved in producing hydrogen from wastewater/industrial water treatment are diverse. However, addressing water stress in hydrogen production is crucial, considering the significant water stress caused by industrial and other human activities, as discussed in the previous chapter. While the water volume required for hydrogen production may not be substantial compared to industries like agriculture, it is essential to recognize that access to this resource is limited and varies across different regions and latitudes worldwide.

VI. THE IBERIAN MARKET (MIBEL)

The Iberian Electricity Market, or MIBEL, stands as a testament to the advantages of cross-border energy market integration. Operating as a single market for Portugal and Spain, MIBEL enables consumers to choose from a range of energy producers and suppliers, fostering healthy competition. The market's marginal model sets energy prices based on the marginal cost of production, with electricity prices determined by the point of intersection between supply and demand (14)

While the integrated market offers significant benefits, it is not without its challenges. The current marginalist market model may pose risks, particularly with increasing renewable energy production leading to declining wholesale prices. To maintain the financial viability of energy producers' investments, the market model may require adjustments to ensure sustainable and competitive operations. Governments have introduced auctions to encourage renewable energy investment and stabilize energy prices, while also adopting hedging strategies to mitigate price fluctuations on consumers' bills (14).

Figure 5 demonstrates the interplay between the variable cost of gas production and electricity prices, highlighting the importance of managing energy resources in a manner that supports sustainability and competitiveness within the Iberian Electricity Market. A balanced approach, considering the nuances of the energy landscape and addressing challenges related to renewable energy, pricing, and investments, is crucial for the enduring success of the MIBEL market.

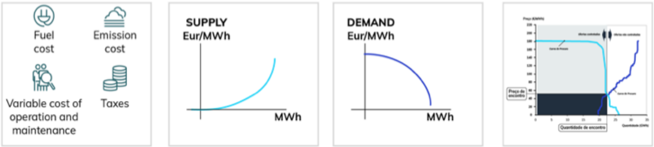


Figure 5. Description of the marginal market model
Source: (EDP, 2022)

VII. METHODOLOGY

The methodology employed involved a process that encompassed optimization using linear programming and the simulation of the best scenario for hydrogen production using just PV panels as renewable energy source and energy from the grid. Each step was crucial in achieving optimal results.

A. Data Collection - Solar Radiation

To initiate the optimization process, data on solar radiation levels in Lisbon, Portugal, were collected. The focus was on obtaining a comprehensive understanding of solar radiation patterns throughout the year. Specifically, the average solar radiation data for each month over the past years were gathered. This data served as a key input for the optimization model, allowing for the determination of the optimal configuration of solar panel installations. The information used will be attach to the Annex I

- Radiation data (European Commission)
- Temperature data (meteoblue, 2023)
- Price data (GlobalPetrolPrices.com, 2022)

Incorporating Cost Data:

In addition to solar radiation data, cost data related to the installation of solar panels was collected. This data included the expenses associated with purchasing and installing solar panels. By incorporating cost data into the simulation, the optimization model could evaluate different installation scenarios and determine the most cost-effective solution for hydrogen production.

Simulation of the Best Scenario:

The optimization model, driven by solar radiation data and cost considerations, simulated the best scenario for hydrogen production using renewable energy. The model aimed to identify the optimal combination of solar panel installations and grid electricity consumption, with a primary focus on prioritizing hydrogen production. By evaluating different configurations and scenarios, the model determined the most efficient and cost-effective solution for maximizing hydrogen generation.

For the methodology of the energy management system development, initial data were collected from three commercial solar panel references with the following specifications:

Reference A: KIT Solar TR Bifacial
Power 550 W
Area 2,7 m2
Efficiency 0,2055
Price (includes Inverter) 250 EUR

Reference B: Kit De Autoconsumo Solar Monofásico De 1kW XS Com Excedentes
Power 1000 W
Area 6,0 m2
Efficiency 0,2
Price (includes Inverter) 905 EUR

Reference C: XUNZEL AD500
Power 500 W
Area 0,9 m2
Efficiency 0,2
Price (includes Inverter) 905 EUR

The reference electrolyzer was obtained from the technical datasheet of the HyProvideTM A-Series electrolyzer developed by Green Hydrogen Systems, featuring the following specifications:
Hydrogen production
Nm3/hour = 30
Kg/Hour= 2,7
Stack at 100% load
Power consuption (KWh/Kg)= 50,1
Efficency: 85%

Assumptions:

The model was constructed based on the following:

- The water source is assumed to be unlimited and free of cost, sourced from an industrial water treatment plant already installed and operational.
- Two hypothetical scenarios were considered: the first assumes no space restrictions for the installation of solar panels, and the second assumes a hypothetical space constraint of 1000m2
- For this analysis it was assumed that 65% of the grid mix comes from renewable energy

B. Formulation

To determine the power generated in watt-hours (Wh), we utilized the following data for each solar panel:

- Power: This refers to the maximum power output of the solar panel in watts.
- Area: The area in square meters occupied by each solar panel.

- Efficiency: The efficiency of the solar panel, denoting the ratio of output power to input power.

The Equation (1) Utilizing the irradiation data where:

a= Radiation data
b= Area m^2
c= Efficiency W

$$(1)\ MIN(a * b * c)$$

This allowed us to extract the hourly power generation data for each solar panel.

Subsequently, we proceeded to calculate the Levelized Cost of Electricity (LCOW) for each panel, considering the following parameters:

- Panel + Inverter Cost: The combined cost of the solar panel and the inverter required for the system.
- Annual Maintenance (% of Initial Cost): This refers to the percentage of the initial cost of the panel that is allocated for its yearly maintenance.
- Year Energy Generated (kWh): The total energy generated in kilowatt-hours over a specific year.
- Years for Full Depreciation (Linear): The period over which the system depreciates fully, considered to be 5 years in our analysis.

In the Equation (2) the computation of the Levelized Cost of Electricity (LCOE) involved he following:

a=Panel
b=Inverter cost
c=Annual maintenance
d= Years for full depreciation
e= Year energy generated

$$LCOE = \frac{a + b + c * d}{e}$$

C. *Optimization of Energy Generation:*

The application of linear programming techniques was instrumental in optimizing hydrogen production, considering constraints and objectives. Utilizing a 1,000m2 space constraint and an unrestricted scenario, we aimed to minimize energy generation costs while achieving maximum hydrogen production with a 100% operational stack. The specifications of the electrolyzer are detailed in Annex II.

Constraints established for the optimization process included limiting the panels to 80% of the available space, using integer values, meeting, or exceeding the electrolyzer's 24-hour consumption, and supplementing non-production hours with grid energy.

The objective function Total Cost Generation was formulated as the sum of the Total Levelized Cost of Electricity (LCOE) for Generation per day. This was derived from the product of the Daily Generation per unit and the number of panel units, and further multiplied by the LCOE of each panel. The Simplex LP solving method was employed to identify the optimal panel configuration, minimizing energy generation costs while meeting constraints.

The subsequent step involved computing the Optimized Generation Profile Panels Selected and weighted LCOE. Hourly power generation data for each panel was determined, leading to the calculation of the Total Generation (KWh)/day. By dividing the Total Cost Generation per day by the total generation per day, the Levelized Cost of Electricity (LCOE) in $/kWh was computed, enabling a comprehensive assessment of the energy generation system's cost efficiency and overall performance.

D. *Economic Analysis and Indicators*

In our economic analysis, we focused on the daily production profile, computing Consumed immediately from own generation (Wh), surplus (Wh), and deficit (Wh) for each hour, considering the system's energy production in Wh (Weighted Gen) and the electrolyzer's demand in Wh at a 100% stack. This enabled the determination of the Surplus that goes to the grid and the Grid purchase to satisfy the Demand Deficit.

With the derived LCOE $/kWh, we evaluated the Electricity Production Cost per kWh, Grid Cost per kWh, and Grid Revenue per kWh, facilitating the assessment of the panel system's hourly production costs and grid purchases required. We also considered the revenue from the Surplus Grid Revenue.

Based on this approach, we established key performance indicators, including:

Self-Consumption
Percentage of Renewables in Grid Supply
Renewables Penetration
Self-Sufficiency/Sustainability
Local Electricity Generated (kWh/day)
Electricity Bought From the Grid (kWh/day)
Electricity Sold to the Grid (kWh/day)
Daily Cost of Electricity Generated
Daily Cost of Grid Purchases
Daily Sales to the Grid
Net Daily Cost (Generation + Grid + Electrolyzer)
Daily H2 production with local solar panels (Kg)
Net cost per Kg H2

These indicators provide a comprehensive overview of the system's performance, offering insights into energy efficiency, cost management, and overall sustainability. They serve as crucial metrics for assessing the economic viability and operational effectiveness of the green hydrogen production system, aiding in informed decision-making and further analysis.

VIII. RESULTS AND DISCUSSION

The outcomes of integrating green hydrogen production in industrial wastewater treatment plants. It explores the technical and economic feasibility under diverse scenarios, aiming to illuminate potential benefits and challenges. The findings contribute to understanding the practical implications of green hydrogen in industrial energy management.

A. Scenario 1

In table 1 its shown the results of the optimization, is assumed no space constraint and prioritize the maximum hydrogen production at the lowest possible energy cost with the provided solar panel specifications

Table 1. Optimization of energy generation scenario 1

Optimization of Energy Generation						
Technology	Daily Generation per unit (Whr)	Number of Units	Generation	Max Number of Units	LCOE (kWh)	Total LCOE Cost of Generation/ Day
Solar Panel 1	3085	1053	3247992	2989	€ 0,07	216,37€
Solar Panel 2	6731	0	0	1333	€ 0,11	€ -
Solar Panel 3	987	0	0	9090	€ 0,75	€ -
Area of Panels m^2		2817,8				
Total Generation (Khr)			3.248		**Total Cost Generation (€)**	**216,37**

Source: Created by the author

Under scenario 1, the hydrogen production with the local installation is described in table 2

Table 2. Hydrogen generation with local solar panels Scenario 1:

Hydrogen Generation				
Technology	Production		Stack 100%	
Electrolycer	Nm3/hour	Kg/Hour	Power consuption (KWh/Kg)	Efficency %
	30	2,7	50,10	85%
H2 Generation with local solar panels Kg			**64,83**	

Source: Created by the author

In the table 3, the data presented showcases several key performance indicators and metrics related to the energy generation and consumption in the system. The self-consumption rate stands at 18%, implying that the portion of the generated electricity is utilized on-site is not that high. Additionally, the system heavily relies on renewable energy sources, with renewables constituting 65% of the grid supply and a total renewables penetration of 82%, inclusive of the grid's renewable portion. The level of self-sufficiency or sustainability is estimated at 49%, indicating a considerable degree of independence in energy generation. In terms of electricity specifics, the system generates an impressive 3247.99 kWh of electricity daily, while sourcing 612.36 kWh/day from the grid and selling 2657.96 kWh/day back to the grid. The cost dynamics illustrate a daily cost of €216.37 for electricity generated, €112.30 for grid purchases, and €239.22 from sales to the grid. The net daily cost, considering generation, grid usage, and electrolyzer expenses, amounts to €89.45. The system produces 64.83 kg of hydrogen daily at a net cost of €3.34 per kg. These figures collectively highlight the system's efficient renewable energy utilization and its effective integration with the grid, resulting in a sustainable and cost-effective hydrogen production process.

Table 3. Performance indicators for scenario 1

Performance Indicators	
Self Consumption	18%
Percentage of Renewables in Grid Supply	65%
Renewables Penetration (Including grid renewable portion)	82%
Self Sufficiency/sustainability	49%
Local Electricity Generated (kWh/day))	3247,99
Electricity Bought From the Grid (kWh/day)	612,36
Electricity Sold to the Grid (kWh/day)	2657,96
Daily Cost of Electricity Generated	216,37 €
Daily Cost of Grid Purchases	112,30 €
Daily Sales to the Grid	239,22 €
NetDaily Cost (Gen+Grid+Electrolyzer)	89,45 €
Daily H2 production with local solar panels (Kg)	64,83
Net cost per Kg H2	3,34 €

Source: Created by the author

B. Scenario 2

As table 4 shows, In this scenario it was add a constrain of space of 1.000m2 taking in consideration that just 80% of this space is usable, and prioritize the maximum hydrogen production at the lowest possible energy cost with the provided solar panel specifications.

Table 4. Optimization of energy generation scenario 2

Optimization of Energy Generation						
Technology	Daily Generation per unit (Whr)	Number of Units	Generation	Max Number of Units	LCOE (kWh)	Total LCOE Cost of Generation/ Day
Solar Panel 1	3085	298	919185	298	€0,07	€61,23
Solar Panel 2	6731	0	0	133	€0,11	€-
Solar Panel 3	987	3	2873	909	€0,75	€2,16
Area of Panels m^2		800				
Total Generation (Khr)			922		**Total Cost Generation (€)**	**63,40**

Source: Created by the author

Under scenario 2 the hydrogen production with the local installation is described in table 5

Table 5. Hydrogen generation scenario 2

Hydrogen Generation				
Technology	Production		Stack 100%	
Electrolycer	Nm3/hour	Kg/Hour	Power consuption (KWh/Kg)	Efficency %
	30	2,7	50,10	85%
H2 Generation with local solar panels Kg			**18,44**	

Source: Created by the author

The data shown in the table 6 reveals several key performance indicators in the context of the energy generation system. Notably, the system demonstrates a moderate level of self-consumption at 54%, indicating a substantial reliance on the grid supply for power consumption. Additionally, the renewables penetration, including the grid renewable portion, is at an impressive 80%, underlining the substantial integration of renewable energy sources into the overall grid framework. Furthermore, the data highlights a self-sufficiency rate of 41%, reflecting a moderate degree of independence in sustaining the energy requirements. The local electricity generated daily amounts to 922.06 kWh, which is considerable but slightly surpassed by the electricity purchased from the grid at 703.81 kWh, suggesting some reliance on external sources for power supply. However, the system compensates by selling 423.46 kWh of excess electricity to the grid, potentially generating additional revenue.

Regarding costs, the daily expense for electricity generated amounts to €63.40, while the cost of grid purchases is notably higher at €131.37, leading to a net daily cost of €156.66, emphasizing the need for more effective energy management strategies to reduce expenditure. On a positive note, the daily sales to the grid provide a partial offset at €38.11, mitigating the net cost. Notably, the system produces 18.40 kg of H2 daily at a net cost of €3.44 per kg, indicating the potential viability of green hydrogen production within this energy framework.

Table 6. Performance indicators Scenario 2

Performance Indicator	
Self Consumption	54%
Percentage of Renewables in Grid Supply	65%
Renewables Penetration (Including grid renewable portion)	80%
Self Sufficiency/sustainability	41%
Local Electricity Generated (kWh/day))	922,06
Electricity Bought From the Grid (kWh/day)	703,81
Electricity Sold to the Grid (kWh/day)	423,46
Daily Cost of Electricity Generated	€63,40
Daily Cost of Grid Purchases	€131,37
Daily Sales to the Grid	€38,11
NetDaily Cost (Gen+Grid+Electrolyzer)	€156,66
Daily H2 production with local solar panels (Kg)	18,40
Net cost per Kg H2	€3,44

Source: Created by the author

In both scenarios, the electrolyzer operates at full capacity, yielding 64 kg of H2, highlighting system efficiency with abundant water availability and zero water costs. The findings emphasize the critical role of green hydrogen in sustainable energy utilization, revealing the complexities of merging renewable sources with industrial wastewater treatment for hydrogen production. Scenario 1 accentuates the necessity of optimal energy synchronization, yet cautions about reduced solar capacity impact and potential electricity cost escalations. Notably, surplus energy injection into the grid balances the costs, but intensive land use requires enhanced sustainability practices. On the other hand, Scenario 2 stresses innovative energy management due to spatial constraints, emphasizing the importance of diversifying energy procurement strategies to ensure self-sufficiency. Both scenarios demonstrate the potential of green hydrogen production within circular economy principles, aligning with evolving sustainability objectives in Europe's energy market.

C. Challenges in Solar Generation and Electricity Price Fluctuations

The scenarios underscore solar generation's critical role in hydrogen production, exposing vulnerabilities to solar variations and escalating electricity prices. Adaptive measures like energy storage solutions or alternative hydrogen production methods during low solar periods are essential to address these concerns. Implementing flexible contracts, investing in energy efficiency, and exploring diverse on-site energy generation beyond solar panels can ensure stability in volatile electricity markets.

D. Hydrogen Pricing Dynamics and Market Evolution

Understanding the pricing dynamics of hydrogen is crucial as demand surges amid the global decarbonization drive. Influenced by production costs, market demand, and government incentives, hydrogen pricing fluctuates with market forces, demanding adaptable pricing strategies. Industry players need to anticipate these variations, considering renewable energy costs and electrolysis efficiency, to make informed decisions on hydrogen production timing.

E. Integration into Industrial Settings: Wastewater Treatment and Fuel Consumption

Integrating green hydrogen production into industrial settings offers advantages such as reduced natural gas consumption and a minimized environmental footprint. By blending hydrogen with natural gas, industries can gradually shift towards a sustainable energy mix, aligning with broader decarbonization goals. This incremental transition allows industries to adapt to new technologies while minimizing infrastructure modifications, facilitating a pragmatic approach towards sustainability.

F. Challenges of Blending Hydrogen with Natural Gas

While blending hydrogen with natural gas aims to reduce carbon emissions, understanding the differences in energy content is critical. The need for careful planning in integrating hydrogen into existing natural gas infrastructure, considering gas flow rates, density, and distribution networks, is vital to achieve carbon reduction while maintaining energy efficiency. Careful considerations during blending are necessary to ensure the anticipated reduction in greenhouse gas emissions, given the complexities involved in compression and pressure loss during hydrogen transport.

IX. CONCLUTIONS

The growing global interest in hydrogen as a renewable energy alternative has been accelerated by both geopolitical and environmental factors, with the European Union emerging as a key proponent. Despite ambitious targets, the unpredictability of the energy sector and the shift toward alternative heating solutions post-COVID present challenges for immediate hydrogen network establishment. However, the imperativeness of decarbonization emphasizes the vital role of hydrogen in sustainable energy transition, necessitating continued developmental focus.

The findings underscore the potential of green hydrogen production in industrial wastewater treatment plants, emphasizing the need for careful consideration of solar capacity, electricity price fluctuations, and integration into existing industrial processes. Collaborative measures and technological advancements are essential for scaling up green hydrogen production and ensuring long-term competitiveness and resilience in the evolving industrial landscape.

The convergence of strategies between the United States and the European Union through Hydrogen Valleys demonstrates a practical approach to foster hydrogen-driven economies and advance decarbonization goals. Sustained international cooperation, along with clear goal-setting within the EU, remains critical for the durability and success of the hydrogen economy.

Scenario 1 emphasizes the importance of synchronized energy generation and consumption, with surplus energy injected back into the grid. However, substantial land occupancy necessitates meticulous planning. Scenario 2 highlights the need for effective energy management strategies and circular economy principles for enhanced sustainability. Comprehensive assessments are essential to accurately evaluate the environmental benefits associated with blending hydrogen with natural gas, considering the energy content variations and transportation challenges.

For future applications, exploring scenarios with continuous sub-capacity hydrogen production and small-scale wind turbines is advisable, promising enhanced financial sustainability. Optimizing energy consumption and production through advanced energy management strategies is crucial for achieving improved self-sufficiency and cost-effectiveness. Overall, the thesis underscores the significance of optimized energy management, sustainable resource utilization, and strategic policy formulation in fostering a resilient, environmentally conscious, and economically efficient energy landscape aligned with renewable energy sector objectives.

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