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Conference paper

Renewable energy for green Hydrogen production: experimentation and predictive tool

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ABSTRACT

The primary objective of this project is to develop a system for the production of green hydrogen, envisioned as a sustainable and environmentally friendly fuel source for the future. This system aims to store energy in the form of renewable and clean chemical energy. To achieve this goal, the project encompasses a thorough investigation, both theoretical and practical, of a hybrid energy system that integrates solar and wind power.

The proposed production process is designed to function autonomously, relying solely on renewable energy resources such as wind and solar power to drive the hydrogen generation process. The system is equipped with an advanced control mechanism that optimizes efficiency by dynamically managing the input from the hybrid energy sources based on real-time environmental conditions. The core of the production process is electrolysis, a method that decomposes water into hydrogen and oxygen using electrical energy. To enhance this process, a catalyst is employed to reduce the energy required for electrolysis, thereby increasing the system's overall efficiency. This approach not only maximizes hydrogen production but also ensures that the process remains viable and cost-effective, even with the variability inherent in renewable energy sources.

Furthermore, the project aims to create a robust knowledge base from experimental data collected under various operational conditions. This data will be used to develop predictive models capable of estimating hydrogen production under different weather scenarios and optimizing the reliability and performance of the electrolyzer. By simulating conditions such as varying wind speeds and solar radiation levels, these models will enable more precise control and planning, ensuring the system can adapt to changing environmental conditions.

In the broader context, this project serves as a foundational step towards the deployment of green hydrogen as a versatile energy carrier that can be integrated into a variety of applications, from energy storage to transportation. The insights gained from this research could pave the way for larger-scale implementation, contributing to the global transition towards a low-carbon, sustainable energy future.

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1. INTRODUCTION

The challenge facing all nations today is the imperative to transition towards a safer, low CO2-emitting energy system while ensuring continued economic and social progress (*CO2 Emissions in 2022 – Analysis*, s. d.) (Dahmani & Abdessemed, 2023). The key question now is: how can we meet the rising demand for energy while also prioritizing environmental sustainability?

Algeria stands out as the foremost African producer of natural gas, boasting the 10th largest proven reserves globally. The country boasts a network of gas pipelines that facilitate its gas exports, particularly to Europe (with Algeria accounting for 13% of European gas imports). In comparison to the pollution levels of nations like the United States and Germany, Algeria maintains relatively low pollution levels, ranking 36th in terms of CO2 emissions (*United Nations Statistics Division - Environment Statistics*, s. d.).

The rise of concepts such as 'green recovery' and 'green economy,' particularly gaining momentum after the 2008 economic crisis, has spurred Algeria to embark on transition initiatives. Despite the country's current secure position in terms of energy availability, the trend towards hydrogen energy cannot be ignored. However, established processes and storage solutions for hydrogen remain costly.

Therefore, it becomes crucial to kick start the production of green hydrogen derived from renewable sources such as wind and solar energy right from the outset. Hydrogen serves as an ideal complement due to its flexibility in energy flow and storage. The envisioned system revolves around an electrolyser that produces hydrogen using electricity sourced from renewable grids (such as solar power plants, wind farms, and hydroelectric dams). This system includes the storage and transfer of hydrogen, along with a fuel cell or hydrogen cell for converting hydrogen back into electricity.

Numerous research centers and laboratories are actively engaged in addressing this crucial issue, aiming to pave the way for a sustainable and greener energy future for Algeria.

Many researches have been made, in Algeria, to assess the ability of producing Hydrogen. The interest started in the beginning of 21 st century, in (« Potentialities of Hydrogen Production in Algeria », 2008) a potential of Algeria in Hydrogen production was exposed and demonstrated showing a promising prospect. The most completed experiences and studies were about the use of solar energy in Algerian Sahara (Derbal-Mokrane et al., 2021), (Khelfaoui et al., 2021), (Bentoumi et al., 2024). Some research has also been conducted to estimate Algeria's potential in terms of utilizing wind energy for hydrogen production (Messaoudi et al., 2024). It is estimated at 1.066 Gt/year, covering an area of 730,719 km2. In only Algerian Sahara by De Wind D8. The maximum production of 113.99 tH2/yr is observed in Adrar (Douak & Settou, 2015). In the Hybridation aspect (Blal et al., 2018) the study has revealed Algeria's significant potential for hydrogen production from wind and solar energy, particularly at the Adrar site. Notably, Adrar is recognized as an area of excellence for wind energy generation, while Tamanrasset is renowned for its solar radiation. The fuel cell serves as a mechanism to convert the chemical energy stored in hydrogen and oxygen, derived from surplus renewable energy, directly into electricity. However, the hybridization process is not comprehensive, as only photovoltaic energy is utilized for hydrogen production. And the North of Algeria wasn't tested in producing green-Hydrogen.

(*Approche Bayésienne expérimentale pour l'analyse des risques*, s. d.)As a complementary approach to the experimental work, the data collected can be utilized to develop a deeper understanding of the optimal conditions for hydrogen production. Several methodologies are available for building such models, including machine learning, data analysis (Lehmann et al., 2020) (Chennoufi & Chakhrit, 2024), and statistical techniques (Clyde et al., s. d.). Among these, the Bayesian approach stands out as a well-established method for integrating prior knowledge with observed data to make probabilistic predictions

(Guetarni et al., 2019), (*Approche Bayésienne expérimentale pour l'analyse des risques*, s. d.) (Djemai et al., 2024). This approach will be employed in this context to enhance the predictive capabilities of the system. By using the Bayesian method, we can create a robust model that not only captures the relationship between environmental variables such as wind speed, solar radiation, and temperature and hydrogen production but also quantifies the uncertainty associated with these predictions. This model will allow for continuous learning and adaptation as more data is collected, refining its accuracy and reliability over time.

2. HYDROGEN PRODUCTION PROCESS

There are manly two types of Hydrogen process, the first one is based on gazs transformation and the second on water defragmentation.

2.1 Steam-methane reforming (SMR)

Stands out as a predominant method for commercial hydrogen production. This process involves reacting high-temperature steam with methane under pressure, facilitated by a catalyst, to yield hydrogen, carbon monoxide, and a minor amount of carbon dioxide. Natural gas is the primary methane source for SMR in industrial facilities and refineries, although alternative sources like landfill gas, biofuels, and petroleum fuels are also considered.

2.2 Electrolysis

Another significant method, utilizes electricity to split hydrogen from water, a process commonly demonstrated in high school science classes. On a larger scale, referred to as power-to-gas, electrolysis is a clean process, producing only hydrogen and oxygen without by-products or emissions.

Ongoing research explores additional hydrogen production methods, such as thermochemical processes converting biomass, photolytic processes using solar energy, and biological processes involving microbes like bacteria and microalgae. The U.S. Department of Energy supports source-neutral hydrogen production pathways, avoiding a color-coded classification based on hydrogen source, production technology, or carbon capture, in contrast to certain industry practices (Ji & Wang, 2021).

3. HYDROGEN CLASSIFICATION

Even if Hydrogen is a gas without color, yet there exist approximately nine color designations to characterize hydrogen. These color codes are indicative of the origin or method employed in its production. The color designations for hydrogen include: green, blue, grey, brown or black, turquoise, purple, pink, red, and white. These color codes serve as distinctions within the energy sector to categorize different types of hydrogen. Below are the color codes for hydrogen along with their respective definitions (*Hydrogen Colours Codes,* s. d.):

Green Hydrogen: Hydrogen produced without any CO2 emissions.

- Blue Hydrogen: Hydrogen generated with CO2 emissions, but with the CO2 sequestered, stored, or converted in some manner.
- Grey Hydrogen: Hydrogen produced with CO2 emissions, typically from Steam Methane or brown coal refining.
- Black or Brown Hydrogen: Hydrogen produced through coal gasification.
- Pink Hydrogen: Hydrogen produced using renewable energy sources.

Green hydrogen is the exclusive type generated in a climate-neutral process. Its extraction method avoids the emission of greenhouse gases (GHG), aligning with its name, and prioritizes sustainability and environmental friendliness. The primary tool employed for the production of green hydrogen is an electrolyser. These devices leverage electricity to separate water into hydrogen and oxygen. A crucial aspect of this green hydrogen production method is that the electricity powering the electrolyser is sourced from renewables like wind and solar, ensuring a lack of associated GHG emissions.

In this project, our proposal revolves around the creation of green hydrogen derived from a hybrid mix of renewable energy sources.

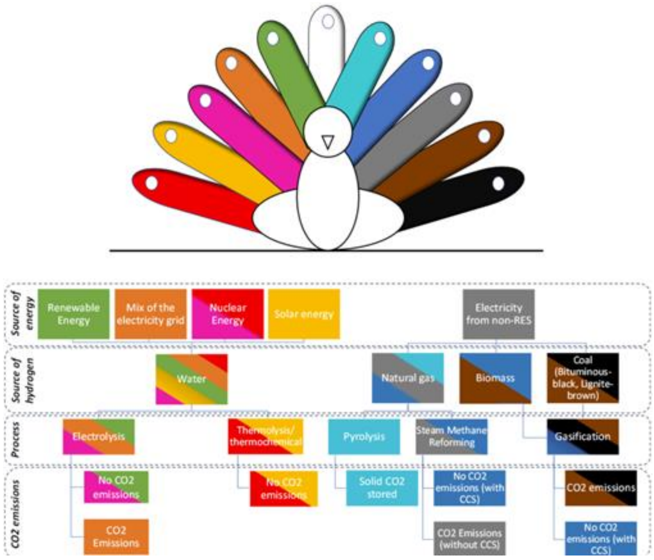

Fig 1. Hydrogen Colors (Incer-Valverde et al., 2023)

4. THE DEVELOPED PROCESS

In the present project, the production of green hydrogen by water electrolysis is considered. The energy input for water dissociation is provided by a hybrid system (PV WIND). The average production per photovoltaic panel per day is assessed. There are four sources of energy: wind energy, solar energy, batteries, and hydrogen. The wind speed is converted into mechanical energy and then into variable electrical energy depending on the wind speed. The solar panel captures solar radiation and transforms it into variable electrical energy depending on sunlight. This energy produced by the renewable energy hybrid system can be converted into alternating current electrical energy if it is to be injected into a distribution network (figure 2).

Alternatively, it can be transformed into chemical energy for storage in batteries and hydrogen production through an electrolyzer. The hydrogen can then be stored or transported as a sustainable storage method.

4.1 Project timeline

The project began by selecting the optimal position for the PV solar panels within the institute, based on an analysis of solar radiation and its direction. This analysis ensured that the PV panels were positioned to capture the maximum amount of sunlight throughout the day.

The second phase involved selecting an appropriate wind turbine and overseeing its installation. A domestic turbine with a power output of 400W was deemed optimal for our prototype, providing efficient energy generation. To handle excess energy production, a charge controller was installed to regulate the flow and store the surplus energy in a battery for later use.

In the third step, a battery system was integrated, connected to both the solar panel and wind turbine regulators to store the energy produced by the system.

Following this, an electrolyzer was designed and constructed. This electrolyzer converts water into hydrogen, with its water level and hydrogen production carefully monitored and controlled by a programmable logic controller (PLC). To enable remote monitoring and control, a PLC was integrated into the overall system. The control logic was programmed into the PLC, allowing real-time supervision of the entire energy production and storage system.

Finally, an experiment was conducted to test the performance of the system under real-world conditions, gathering data on energy production, storage efficiency, and system reliability

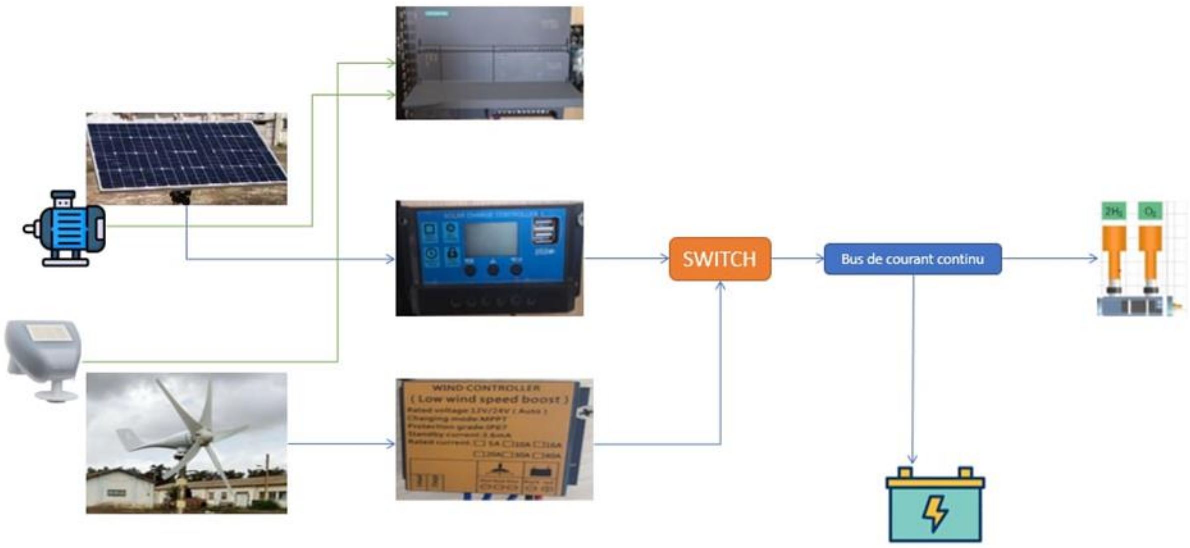

Fig 2. Prototype architecture

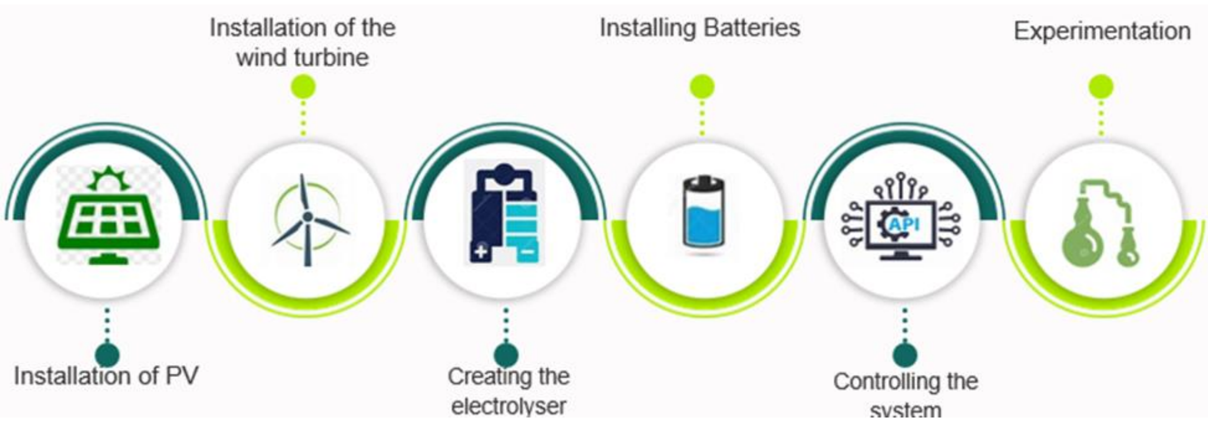

Fig 3. Prototype architecture

4.2 Installation of PV system

For the installation of the photovoltaic (PV) system, a platform was constructed with a barrier positioned 160 centimeters above the ground to mitigate the effects of high wind speeds, providing stability to the panels. Following the construction of the platform, the optimal direction and position of the sun were studied throughout the day at Es-Senia, specifically at the IMSI Instrumentation Lab (Figure 4). To accurately track the sun's position during the day, satellite-based localization (GPS) was utilized to establish the axes of the sun's movement. This data allowed for precise alignment of the PV panels, ensuring they captured the maximum amount of solar radiation during different times of the day. The sun's trajectory refers to the apparent daily and seasonal path it follows in the sky. Due to the Earth's rotation and orbit, this path takes an arc-like shape, with significant variations throughout the year. Understanding this trajectory is essential for optimizing the tilt and orientation of the PV panels, maximizing energy capture during both summer and winter months.

By aligning the PV panels based on these calculations, the system can effectively harness solar energy, improving the efficiency of the energy production and storage process.

Fig 4. Position of the Lab

4.3 Installation of the wind turbine

For the installation of the wind turbine system (Table 1), a concrete platform was constructed with a two-meter barrier from the ground to elevate the turbine, improving its ability to capture high-speed winds. This elevation helps reduce the effects of ground turbulence and ensures the turbine operates in a more consistent wind flow, which is crucial for maximizing energy generation. After the platform's construction, a detailed study was conducted to analyze the optimal wind direction and speed throughout the hours of the day. Wind patterns were monitored using anemometers and wind vanes to collect data on wind speed and direction at various times, ensuring that the turbine was positioned to harness the most consistent and powerful winds. Understanding the local wind dynamics is critical for the turbine's efficiency. Winds tend to vary not only throughout the day but also seasonally. By determining the predominant wind directions and the times of day when wind speeds are optimal, the wind turbine can be positioned and angled to capture the maximum possible energy.

This analysis of wind patterns allows for improved performance of the wind energy system, reducing downtime and increasing energy output. The turbine's position, height, and orientation were all carefully calibrated based on these findings to ensure maximum efficiency in energy generation.

Table 1. Wind Turbine Caracteristique

Model	400
Rated Power	400 W
Blade Number	5
Rated Voltage	12 V

To detect and measure wind speed, a wind sensor (wind turbine-motor) was developed and calibrated with the anemometer sensor from the National Weather Office (ONM) in Oran.

4.4 Hybridation and control

To stabilize the energy generated from both the wind turbine and photovoltaic (PV) system, two regulators are employed. These regulators are responsible for managing the energy flow from each source and ensuring stable output. Both regulators are connected to the central programmable logic controller (PLC). Sensors are also integrated into the system and connected to the PLC, allowing real-time monitoring and data collection. These sensors help the system determine whether the energy from the wind turbine or the PV system should be stored in the battery or directed to the electrolyzer for hydrogen production.

Figure 06 displays the Human-Machine Interface (HMI) used for system supervision. The HMI provides real-time indicators, allowing operators to monitor the performance of the energy sources, battery levels, and the hydrogen production process. Through this interface, users can observe system status, energy flow, and adjust settings as necessary, ensuring efficient and effective energy management.

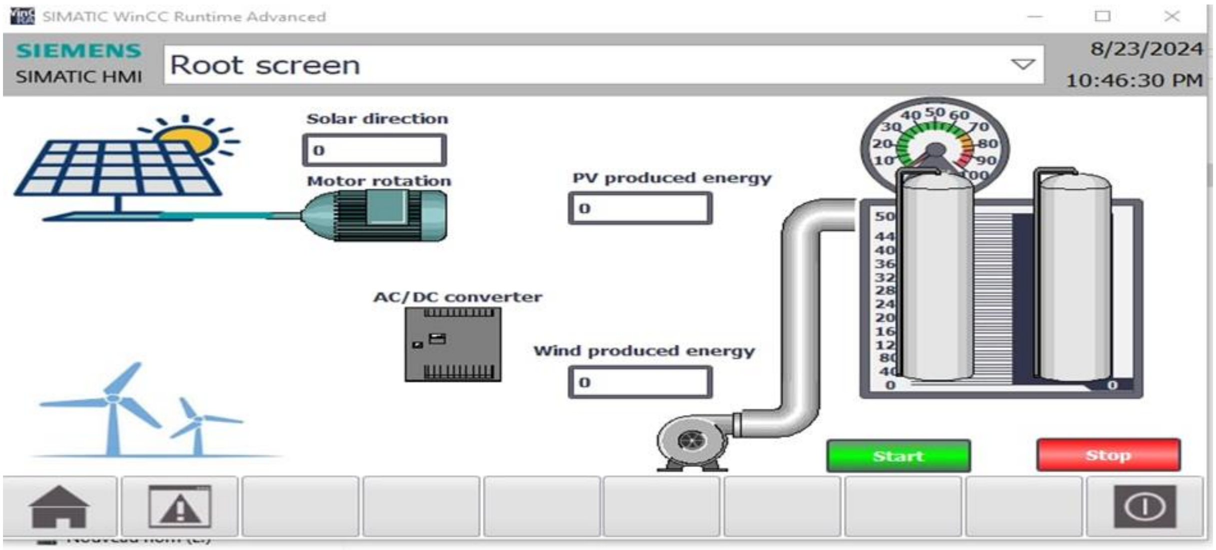

Fig 6. Position of the Lab

4.5 Electrolyser

The electrolyzer consists of a glass container with dimensions of 28.8 cm x 21.6 cm x 23.3 cm. Inside, the cathode and anode are separated by a distance of 11 cm to ensure effective electrolysis. To facilitate the electrolysis process, the water inside the electrolyzer is mixed with a catalyst, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), which lowers the electrical resistance of the water and improves the efficiency of hydrogen production. The electrolyzer operates by applying an electric current through the water, causing it to split into its constituent gases hydrogen at the cathode and oxygen at the anode. The separation of the cathode and anode ensures that the gases do not recombine and are collected in separate chambers.

The design of the glass container allows for easy observation of the electrolysis process, and its dimensions were carefully chosen to optimize the amount of hydrogen produced relative to the power input. The use of a catalyst is essential to reduce energy consumption and increase the rate of hydrogen production, making the process more efficient.

5. EXPERIMENTATION AND RESULTS

The experimentation was conducted on a sunny day with favorable weather conditions, ensuring optimal performance of both the solar and wind energy systems. The temperature was approximately 28°C, ideal for solar energy production as photovoltaic panels typically perform efficiently at moderate temperatures. The wind direction was predominantly from the northeast, with wind speeds ranging between 12 and 28 km/h. These conditions were particularly well-suited for the hybrid renewable energy system being tested. The sunny weather provided consistent solar radiation, allowing the photovoltaic panels to generate a steady supply of electricity. At the same time, the wind turbine was able to harness the northeast winds efficiently, operating within its optimal speed range to produce additional energy. This combination of solar and wind power ensured that the electrolyzer had a continuous and stable supply of electricity to power the electrolysis process.

Throughout the experiment, the system's control unit monitored both energy sources and adjusted the flow of power to the electrolyzer and storage components. The catalyst-enhanced electrolyzer performed well under these conditions, efficiently converting water into hydrogen and oxygen. The real-time data collected from the sensors, combined with the favorable environmental conditions, provided useful insights into the system's overall efficiency and areas for potential optimization.

Further experimentation in varying weather conditions will be necessary to assess the robustness and adaptability of the system across different environmental scenarios, such as during cloudy days or periods of lower wind speeds. This will help ensure that the system can operate efficiently year-round, regardless of fluctuations in solar radiation or wind availability.

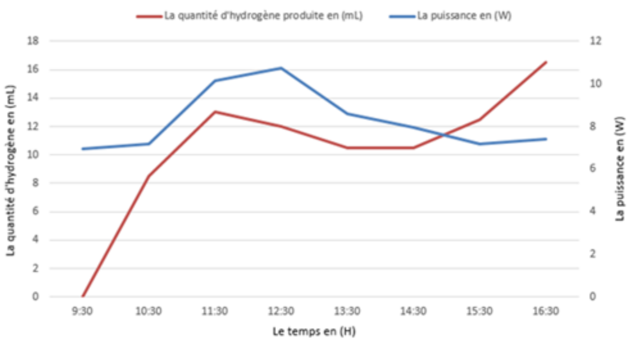

Fig 4. Produced Hydrogen using PV energy

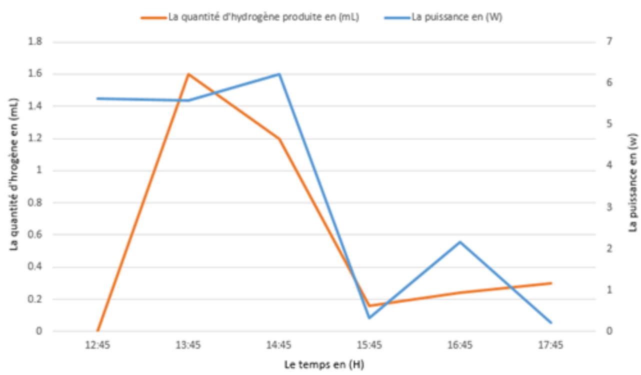

Fig 5. Produced Hydrogen using wind turbine energy

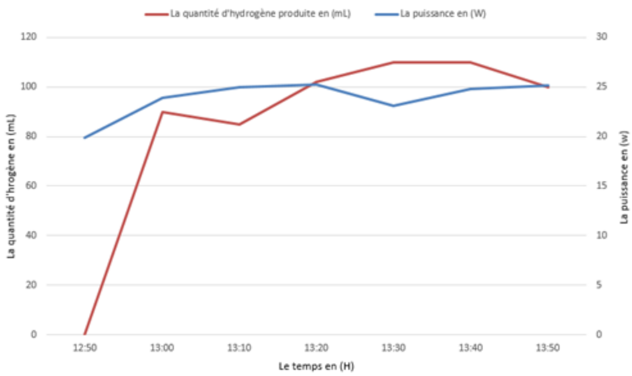

Fig 6. 1 hour of hybridation and catalyser use

The quantity of produced hydrogen is more accurate and stable when using PV. However, wind turbine energy can compensate for the lack of luminosity. The catalyst used maximizes the efficiency of the electrolyzer and should be adopted in such a system.

The results from these experiments can serve as a valuable knowledge base. This data repository can be leveraged to build predictive models that estimate the potential hydrogen production under specific weather conditions, as well as to assess the reliability and efficiency of the electrolyzer system over time.

Various methods are employed to extract meaningful insights from stored data (Aissani et al., 2014), including classifiers, machine learning algorithms, and other advanced data mining techniques. These tools are essential for transforming raw data into actionable knowledge that can be used to optimize systems and predict future outcomes. Among these techniques, the Bayesian approach was selected for experimentation in this project. The Bayesian approach is particularly well-suited for this application because it provides a probabilistic framework for making predictions based on prior knowledge and observed data. In the context of this project, Bayesian methods can be used to develop predictive models that estimate the quantity of hydrogen production under specific weather conditions and assess the reliability of the electrolyzer over time. By integrating the experimental data into a Bayesian model, it is possible to update predictions dynamically as new data is collected. This allows for real-time adjustments to the system, such as modifying the operation of the electrolyzer or optimizing energy distribution between the wind and solar sources, based on changing environmental conditions. Moreover, Bayesian methods can quantify uncertainty, providing a range of possible outcomes rather than a single deterministic prediction. This is particularly valuable in renewable energy systems, where variability in weather conditions can significantly impact energy production.

Bayesian networks are probabilistic graphical models that represent variables and their conditional dependencies through directed acyclic graphs (DAGs). Each node represents a random variable, and directed edges indicate probabilistic relationships. Using Bayes' theorem (1), these networks allow for the updating of probability estimates as new evidence becomes available (Aissani et al., 2018).

$$Pr_E(H) = \frac{Pr(H)\,Pr_H(E)}{[Pr(H)\,Pr_H(E) + Pr(-H)\,Pr_{-H}(E)]} \qquad (1)$$

The hypothesis H, Pr(H) call this the prior probability of H, probabilities to the obtained evidence E conditionally on the truth of H, PrH(E), and conditionally on the falsehood of H, Pr−H(E), the probability of the hypothesis H conditionally on the evidence E

A key advantage of Bayesian networks is their ability to handle missing data and incorporate prior knowledge, enabling robust predictions even with incomplete information. They also model causal relationships, allowing users to assess how changes in one variable affect others. Due to their flexibility in integrating diverse data sources, Bayesian networks have become vital tools in fields such as artificial intelligence, medical diagnosis, and finance, facilitating informed decision-making in uncertain environments.

5.1 Bayesian Model

In the Bayesian network the node is each item and the list of its possible values are the labels of that node. Some modes are continuous data; they will be represented in nodes of continuous values. The decisional node is the produced quantity of Hydrogen "production" This node is the node to predict in this network, so it is at the center of the network as shown in Fig 7.

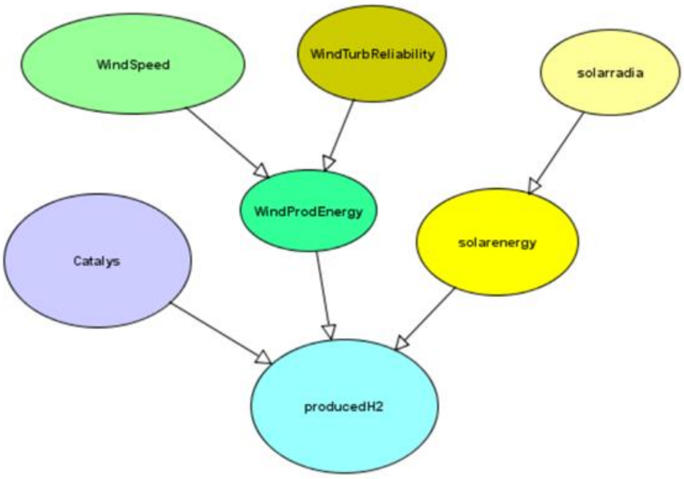

Fig 7. The Bayesian network for Hydrogen production

5.2 The network analysis

Once the network is established and the data is loaded, the system (Figure 8) is ready for comprehensive analysis and the generation of various scenarios. Using this model, several key insights can be drawn:

One significant finding is that under specific weather conditions, wind speeds of 30 km/h and solar radiation intensity of 300 nm the probability of producing less than 10 ml of hydrogen per hour is at its highest. This suggests that while the energy input from both the wind turbine and solar panels is sufficient to initiate the electrolysis process, it may not be optimal for achieving higher rates of hydrogen production. The network model can be effectively used for predictive purposes, allowing for the simulation of various scenarios based on hypothetical weather conditions. For instance, consider a typical weather state recorded in Es-Senia, Oran: wind speed of 45 km/h and solar radiation of 1000 mn (figure 9). When this data is input into the network model and the inference process is launched, the system predicts that the quantity of hydrogen produced by the electrolyzer could reach up to 21 ml per hour under these optimal conditions.

This result indicates that the prototype system, when operating under favorable environmental conditions, has the potential to generate a significant amount of hydrogen. Although 21 ml/h may seem modest on an industrial scale, it demonstrates the prototype's capability and effectiveness at harnessing renewable energy sources to produce hydrogen. This outcome supports the idea that small-scale, localized hydrogen production could be feasible and sufficient for specific applications, such as powering small devices or serving as an educational demonstration of green energy technologies.

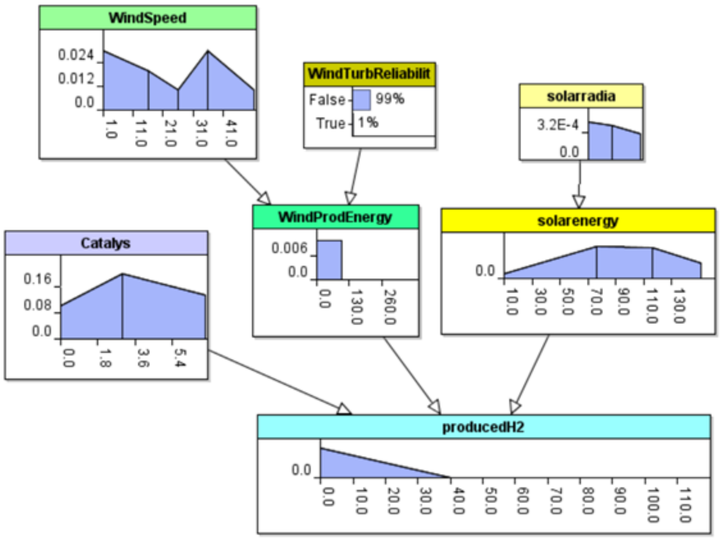

Fig 8. Nodes probabilities

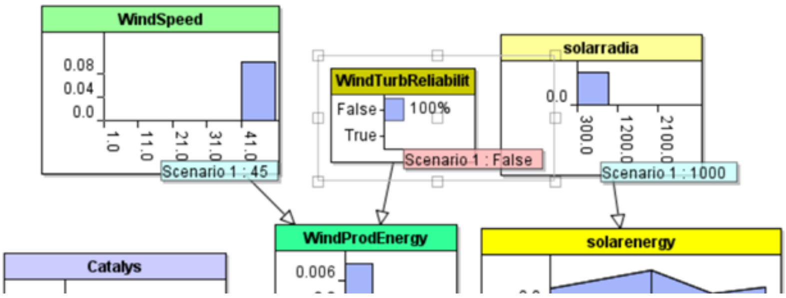

Fig 9. Scenarios simulation

6. CONCLUSION

The proposed hydrogen production process operates autonomously, relying exclusively on renewable energy sources such as wind and solar power. By integrating a wind turbine and photovoltaic panels, the system ensures a stable and sustainable energy supply for the electrolyzer. This hybrid setup is supported by an advanced control system that optimizes energy usage, effectively managing the variable nature of renewable resources to maintain the electrolyzer's peak performance. The core of the production method is based on the electrolysis of water, a process that splits water molecules into hydrogen and oxygen gases using electrical energy. To enhance the efficiency of this process, a catalyst is introduced into the electrolyte solution. This catalyst reduces the electrical resistance of the water, thereby lowering the overall energy consumption required for hydrogen production. The electrolyzer's design characterized by the careful separation of the cathode and anode, along with precise control over the catalyst concentration aims to maximize hydrogen output while minimizing power consumption.

The experimental results so far have been promising, demonstrating that under optimal conditions, the system can produce a significant quantity of hydrogen. This indicates that the prototype is capable of efficiently converting renewable energy into hydrogen, making it a viable solution for small-scale green hydrogen production.

However, there is still significant room for improvement. The electrolyzer can be further refined to increase its efficiency and output. Additional experimentation is essential to better understand the system's behavior under a wider range of environmental conditions and to identify potential areas for optimization.

Moreover, the data collected from these experiments can be utilized to develop predictive models using advanced techniques such as machine learning and Bayesian inference. These models can provide deeper insights into the relationship between environmental factors and hydrogen production, helping to optimize the system's performance further. Predictive modeling could also facilitate the development of larger-scale hydrogen production systems, contributing to the broader deployment of green hydrogen as a sustainable energy carrier.

In conclusion, while the current prototype has shown that it is possible to produce green hydrogen efficiently using renewable energy, continued research and development are necessary to unlock its full potential. By refining the electrolyzer, enhancing the control system, and leveraging data-driven predictive models, the system can be scaled and improved, paving the way for its integration into larger renewable energy networks. This work represents a significant step toward achieving a sustainable, low-carbon energy future, where green hydrogen plays a pivotal role in meeting global energy demands while minimizing environmental impact.

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