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Towards Sustainable Energy: Modeling a modified 50kWp Photovoltaic PEM Electrolysis System for Green Hydrogen in Tegucigalpa

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***Abstract*— The transition towards clean and sustainable energy solutions has become paramount to addressing global environmental concerns and energy security. As part of this imperative, proton exchange membrane (PEM) electrolysis systems for hydrogen production have garnered significant attention. These systems leverage electrical energy to efficiently separate water into its constituent elements, hydrogen and oxygen, without emitting harmful emissions. The hydrogen produced serves as a versatile energy carrier for applications such as clean mobility, energy storage, and industrial processes. This research project aims to model a PEM electrolysis system, exploring its operational dynamics under real environmental conditions. Through modeling, experimentation, and systems analysis, the objective is to assess the results obtained from installing an electrolysis system powered by photovoltaic energy. The MathWorks model "PEM electrolysis system" will be a modified version used to simulate a hydrogen system supplied by a photovoltaic system with a generation capacity of up to 35 KW, showcasing the specific irradiance conditions of Tegucigalpa. It should be noted that the synergy of PEM electrolysis with renewable energy sources holds immense promise for the future development of Latin American countries. As these nations aim to fortify their energy infrastructures and reduce dependence on conventional sources, electrolysis emerges as a clean, versatile, and economically viable solution, utilizing the region's abundant renewable resources to shape a sustainable and prosperous energy future.**

***Key words*— Proton Exchange Membrane (PEM), electrolysis, model, hydrogen**

I. INTRODUCTION

In recent times, the environmental impact of traditional energy sources has attracted global attention. Growing concerns about climate change resulting from the use of these conventional energy sources have led the world to pivot towards sustainable energy solutions. The predominant source of energy for electricity generation, derived from fossil fuels, oil, natural gas and coal, has become increasingly unsustainable [1].These resources are finite, non-renewable and their combustion contributes to the emission of greenhouse gases [2],[3].

To address the threats that non-renewable energy exposes us to, the world is turning to advanced technologies and renewable energy sources. Renewable energy sources are the bet of the future for a world with low greenhouse gas emissions. According to a study carried out in (2022), it was found that in 2020, renewable energies (mainly hydroelectric, wind and solar) accounted for 12.6% of total energy consumption worldwide. However, fossil fuels still accounted for 83% of total energy consumption in that same year [4].

Renewable energy covers a wide range of resources, including hydropower, solar energy, wind energy, biomass, geothermal energy and marine energy. The substantial growth in renewable energy production underscores the need for effective storage solutions [5]. One of the central dilemmas in this area is how to store the surplus energy generated from renewable energy when it exceeds immediate demand [6].

Currently, there are various methods for producing hydrogen, except that they are based on fossil fuels. The predominant approach to meeting the need for energy storage and generation without contributing to carbon dioxide emissions is through water electrolysis. This method, when combined with electricity generated from renewable energy, produces "zero emissions", making it an environmentally sustainable option [7].

Hydrogen, being one of the most abundant elements, has the highest energy-to-mass ratio of any combustible substance on Earth. Its importance as a potential energy vector for the future energy transition cannot be underestimated [8]. To maximize the effectiveness of such systems, hydrogen generation from clean sources, such as solar energy, emerges as a promising avenue, exemplified by photovoltaic (PV) hydrogen systems. some systems, as proposed by *Boulmrharj* [9] and *Pierre* [10], suggest that the thermal energy produced from the fuel cell can be used for heating and cooling in energy-efficient buildings.

In the design of hydrogen photovoltaic systems, efficiency remains a critical consideration. Achieving optimal energy production by the photovoltaic array aligned with the energy requirements for solar hydrogen production is crucial. The primary focus in the paper is on the implementation of the electrical supply of the electrolyzer. The emphasis shifts towards refining the connection between photovoltaic panels and electrolyzer components to enhance the efficiency of green hydrogen production. This research is dedicated to analyzing the interaction between photovoltaic panels and electrolyzer components to achieve the most efficient production of green hydrogen.

In the case of this research, the simulation of the place where the irradiation data will be taken is in Tegucigalpa, Honduras. The model used implies a direct coupling between the electrolyzer and the photovoltaic assembly that will simulate the operation of the hydrogen system if it were in Tegucigalpa. The model used in the paper is shown in the following figure.

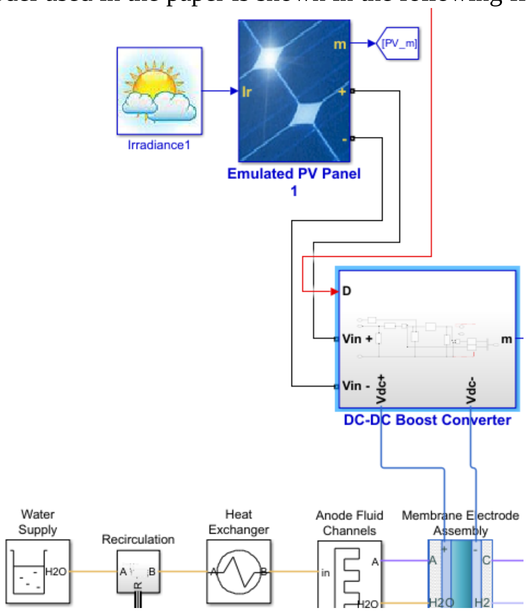

Fig. 1 schematic modified model of solar-hydrogen system

With the configuration of the solar-hydrogen system is important to understand the behavior of the proton exchange membrane. To later conclude if the application of this type of systems is worth installing in the construction of new buildings.

This article is dedicated to the exploration of proton exchange membrane (PEM) electrolyzers and covers a wide range of topics relevant to this electrolyzer technology. The following sections of this article will delve into the modeling and analysis of a photovoltaic electrolyzer hydrogen production system, with a specific focus on component operation and performance.Section II presents the hydrogen production model and the constituent elements of the system, it also details the adaptations made to the modified model. Section III discusses the modeling and analysis of results, and finally, Section IV provides the concluding remarks.

II. MATERIALS AND METHODS

The proton exchange membrane PEM electrolysis system used in the modified model, has as main purpose to harness the power provided by photovoltaic supply (DC) to the PEM to cleave water into its constituent elements, hydrogen and oxygen. The production of hydrogen produced by the membrane dictates the power of the fuel cell to be installed for a later conversion of hydrogen back to electricity. In this following section each part of the elements from the model is described to know how the modified model works.

A. PV Electric Generation

Since the system has the means to produce hydrogen without the intervention of high emitting fossil fuels, the main source that powers the PEM comes from photovoltaic source. The main element which is modified is the PV system, this photovoltaic system has to simulate the irradiation parameters in Honduras.

Changing the main source requires an entire new modification to this element of the system, since the actual model provided by mathlabs uses as electrical supply what a common photovoltaic arrangement produces in a day.

B. Electrolysis of water

To understand what occurs inside the electrolyzer its necessary to know the process of water electrolysis.

Water electrolysis is an electrolytic process in which submerged electrodes are used to pass electrical current through to split it into positive hydrogen ions (H+) and negative oxygen ions (O-), which collect at the cathode and anode, respectively. This process is an efficient way to produce a pure quantity of hydrogen without bad environmental impacts. The process should be better to have an electrical input, which can be supplied by solar and wind sources[11],[12].

C. Proton exchange membrane

The main characteristic of this type of electrolyzer is its solid electrolyte, consisting of a polymer membrane.This ensures the conduction of hydronium ions (H3O+) produced at the anode and allows the separation of hydrogen and oxygen produced.

The advantages of this technology are the compactness, the simplicity of the design of operation, the limitation of the problems of corrosion, and the performances significantly superior to the alkaline type.

The mode of operation of a PEME depends on the use of a solid polymeric electrolyte for transferring protons, one of the most commonly used is nafion. Also, the costly metal catalysts like (platinum, platinum/ruthenium). The catalysts used in the model are intended to match the characteristics of a platinum catalysts that uses the technology of novel titanium thin GDL with well-tunable pore morphologies. The PEM is schematically shown in figure 2.[13]

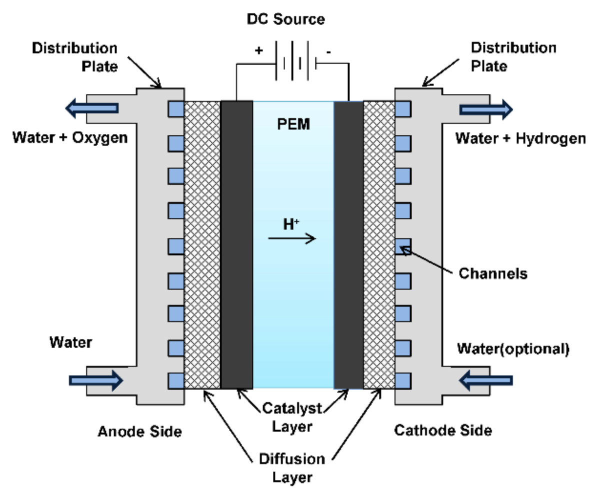

Fig. 2 Diagram of PEM electrolyzer

D. Anode Fluid Channels

In the context of the PEM electrolysis system model, the Anode Fluid Chambers play a pivotal role in facilitating the electrochemical process that leads to the separation of water into hydrogen and oxygen. These chambers serve as essential compartments where water, which is supplied through the thermal liquid network, undergoes a series of transformative reactions. At the heart of the Anode Fluid Chambers is the anode, a critical electrode that initiates the electrolysis process. As electrical current flows through the anode, it triggers the oxidation of water, resulting in the release of oxygen ions (O_2) and electrons (e-). These released oxygen ions are drawn away into the anode moist air network, where they will be subsequently vented, while the electrons contribute to the electrical current[14]The basic reaction occurring throughout the anode can be expressed as given below:

$$Anode: H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^{2-} \ (1)$$

Moreover, the Anode Fluid Chambers are meticulously designed to ensure the efficient separation of gases and fluids, facilitating the smooth flow of water to the anode for continuous electrochemical reactions. In the anode chamber, four moles of oxygen are generated for each electron. According to the "Faraday's law" we can define the molar flow rate of generated oxygen as:

$$N_{an,O_2}^{gen} = \frac{1}{4F}\left[{mol}/{s}\right] \ (2)$$

similarly, two moles of water are consumed for each electron.

$$N_{an,O_2}^{Cons} = \frac{1}{2F}\left[{mol}/{s}\right] \ (3)$$

E. Cathode gas Channels

The Cathode Gas Channels within the PEM electrolysis system constitute another critical component in the intricate process of hydrogen production. These channels are responsible for facilitating the transport and management of the hydrogen-rich gas mixture produced at the cathode side. As hydrogen is generated through electrochemical reactions, it is channeled into these dedicated gas channels, along with any transported water molecules that may have traversed the membrane electrode assembly (MEA). The efficient operation of the Cathode Gas Channels is essential for maintaining the purity and quality of the produced hydrogen. This involves meticulous control and regulation to ensure that the generated gas is free from unwanted water vapor. Additionally, the channels play a role in maintaining the desired pressure conditions within the cathode side, thereby ensuring optimal working conditions for the electrochemical processes. [13].

At the cathode side, hydrogen is generated by the electrochemical reaction. The molar balance and the gas partial pressure can be calculated similarly to the anode side.

$$Cathode: 2H^+ + 2e^{2-} \longrightarrow H_2 \ (4)$$

Product hydrogen is calculated using "Faraday's law" considering that for two moles of electrons one mole of hydrogen is generated:

$$N_{H_2}^{gen} = \frac{1}{2F}\left[{mol}/{s}\right] \ (5)$$

F. Membrane electrode assembly

The Membrane Electrode Assembly (MEA) is a core component in a Proton Exchange Membrane (PEM) electrolysis system. It consists of multiple layers, including a proton exchange membrane, and serves as the primary separator. The proton exchange membrane is typically constructed from a solid polymer electrolyte. The primary function of the MEA is to facilitate the controlled passage of protons (H+) while preventing the flow of electrons (e-) and gases. This selective permeability ensures that the necessary ion-exchange reactions can occur, which are crucial for the generation of hydrogen and oxygen. Additionally, the MEA contributes to maintaining the temperature of the system at the required 80 degrees Celsius, ensuring optimal operating conditions for the electrochemical reactions and hydrogen production. All these elements work together to undergo the water electrolysis process and can be schematically in the next figure[15].

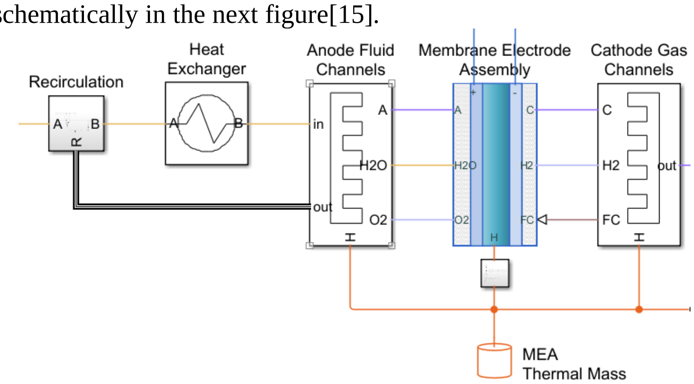

Fig. 3 Membrane electrode assembly

The net reaction resulting from the electrochemical reaction is the following.

$$Net\ reaction: H_2O \rightarrow H_2 + \frac{1}{2}O_2 \ (6)$$

G. Water supply

This component serves as the essential source of water for the electrochemical process. It facilitates a continuous flow of water to the anode, ensuring that the electrolysis process is sustained. Additionally, the water supply manages any excess water and oversees its recirculation to maintain a consistent supply for hydrogen generation. Parameters such as water temperature and purity are considered to optimize the efficiency of the electrolysis process. As water is consumed in the electrochemical reaction at the anode, the water supply component plays a critical role in monitoring and managing the water flow, ensuring the system's smooth operation for efficient hydrogen production.

H. Recirculation

The recirculation system includes two entries, one from the anode and the other from the water supply. Within the recirculation block, a separator tank separates the remaining oxygen (O_2) from water (H_2O), designating it as "L_tank" for recirculation through the water supply. This recirculated water exits through an outer connection to the heat exchanger. The system also integrates a temperature sensor to maintain the water at a constant 80 degrees Celsius, optimizing conditions for anode electrochemical reactions and enhancing overall efficiency.

I. Heat Exchanger

The heat exchanger in the Simulink model combines the characteristics of the incoming water supply and the environment. It models pipe flow dynamics, considering viscous friction losses and convective heat transfer. It can include dynamic compressibility and fluid inertia effects. Ports A and B represent the inlet and outlet, while Port H connects to the pipe wall.

J. Dehumidifier

The dehumidifier in the Simulink model efficiently removes unwanted water vapor from hydrogen, ensuring gas purity. Equipped with a flow rate sensor, it detects and eliminates water vapor.

K. Hydrogen Output

The Hydrogen Output component in the Simulink model features a pressure and temperature sensor. A pressure regulator valve ensures a stable pressure of 3 MPa at the cathode, relative to atmospheric pressure at the anode. The differential pressure across the MEA mitigates electro-osmosis drag, facilitating water transport and reducing water accumulation at the cathode. The produced hydrogen is stored, allowing for accurate measurement of its production.

The model operates by intricately capturing the processes involved in hydrogen production from water electrolysis. Initiated by the Water Supply module and a circulation pump, the model orchestrates water flow dynamics and recirculation. As water traverses the system, the Anode Fluid Channels manage oxygen production, efficiently balancing the electrochemical reactions.

A distinctive feature of this model is the streamlined thermal management—there's no need for a separate cooling network. Excess heat dissipates through recirculating water, and the environment is regulated via the Heat Exchanger, optimizing the system's thermal performance.

The heart of the model lies in the Membrane Electrode Assembly (MEA), a bespoke Simscape™ block representing essential electrochemical reactions. It serves as the nucleus for hydrogen production, embodying the core functionality of the electrolysis process.

The interconnected dynamics continue with the Cathode Gas Channels, Dehumidifier, and the Hydrogen Output component. The Cathode Gas Channels ensure the purity of the produced hydrogen, while the Dehumidifier removes unwanted water vapor. The Electrical Supply is adjusted to align with Tegucigalpa's solar conditions, seamlessly integrating the specific energy production profile.

The final touch is provided by the Hydrogen Output component, equipped with sensors, finalizing the process by efficiently storing and measuring the produced hydrogen.

The primary modification implemented in the model involved adapting the electrical supply profile of the photovoltaic system to align with the meteorological conditions of Tegucigalpa, Honduras. Specifically, the energy production profile was adjusted using data from June 10th as a reference day.

For simulation purposes, a Jinko Solar P-type Mono-crystalline module (JKM550M-72HL4) with a maximum power of 550W and an efficiency of 21.33% was selected. The inverter used was a GE Solar Inverter (GEH10-1U-10) of 10kW. The system consists of 90 panels distributed across four inverters. Three of the inverters feature two strings, each with 11 panels, while the fourth inverter has three strings, each with 8 panels. This photovoltaic arrangement made in "*Open solar version 2.16.0"* is illustrated in Figure 4.

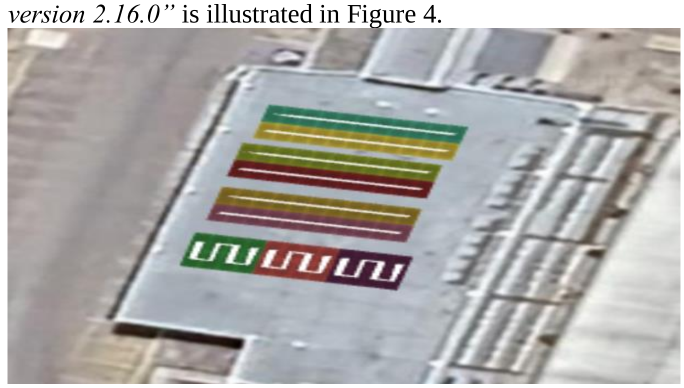

Fig. 4 Photovoltaic system arrangement

The daily energy production data was extracted and integrated into the code of the electrical supply block in the PEM electrolyzer model to simulate its performance under the solar conditions of Tegucigalpa.

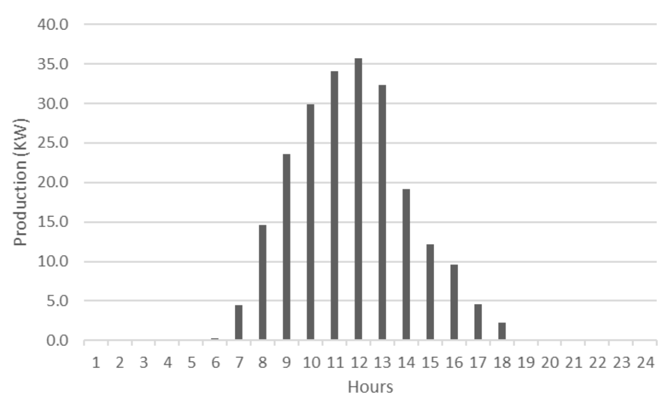

Fig. 5 The PV production during 24 hours

Another significant modification focused on optimizing the membrane electrode assembly (MEA) by adjusting the number of cells in the electrolyzer. This adaptation aimed to enhance the efficiency of hydrogen production in alignment with the real hydrogen production potential of the envisaged photovoltaic system. The following table outlines the pertinent data detailing the composition of the electrolyzer, reflecting the adjustments made to leverage a more efficient utilization of hydrogen production with the anticipated photovoltaic system.

TABLE I. PARAMETERS OF ELECTROLYZER

Parameters	Value	Unit
number of cells in stack	20	
cell area	280	cm^2
Membrane thickness	125	µm
anode gas difusion layer (GDL) thickness	25	µm
Cathode gas difusion layer (GDL) thickness	250	µm
exchange current density	0.0001	A/cm^2
charge transfer coefficient	0.7	
water difussivity in anode (GDL)	0.07	cm^2/s
water difussivity in Cathode (GDL)	0.07	cm^2/s
Density of dry membrane	2000	kg/m^3
Equivalent weight of dry membrane	1.1	kg/mol

III. RESULTS

In this results section, the parameters established in the previous section were employed to examine various aspects of the system. Figure 6 depicts the current-voltage (I-V) curve along with the power consumption of a cell within the stack. The initial ascent in voltage, observed as the current increases, is attributed to electrode activation losses. Subsequently, a gradual voltage upswing occurs due to Ohmic resistances. Notably, at a current density of 2 A/cm^2, the cell voltage stabilizes at approximately 1.71 V.

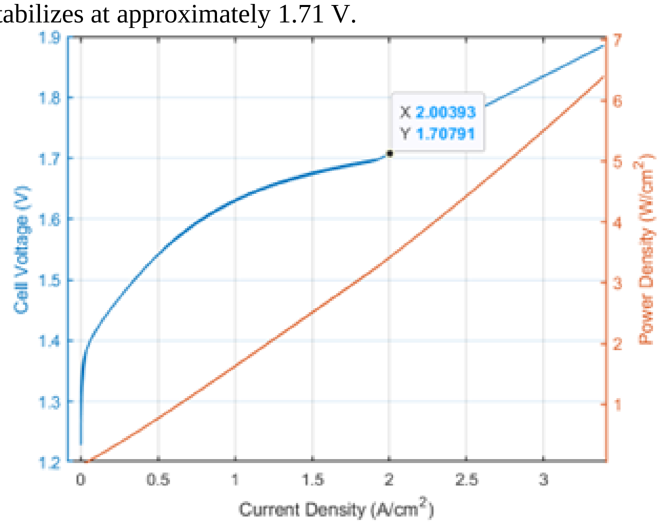

Fig. 6 Fuel Cell I-V Curve

figure 7 shows the electrical power consumed by the electrolyzer as a function of the current density. The power consumption increases linearly with the current density, indicating a constant voltage across the electrolyzer. The graph also shows the power needed to produce hydrogen according to the thermodynamic potential of water splitting. The difference between the electrical power and the hydrogen power is the heat dissipated by the electrolyzer due to various losses, such as activation, ohmic, and mass transport losses.

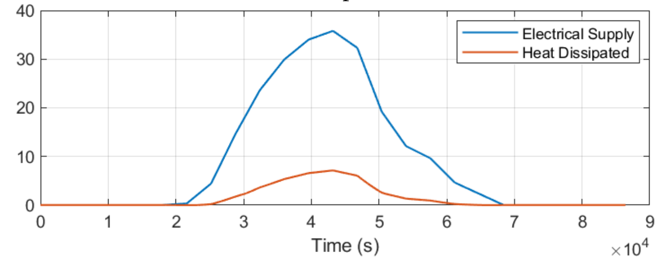

Fig. 7 Power consumed by electrolyzer (kW)

Figure 8 shows the thermal efficiency of the electrolyzer based on both the higher heating value (HHV) and the low heating value (LHV) of hydrogen. The thermal efficiency based on the HHV is higher than the thermal efficiency based on the LHV because the HHV is higher than the LHV. The thermal efficiency of the electrolyzer can be found using the following formula.

$$\eta_{HHV} = \frac{N_{H_2} * HHV}{Pel} \quad (7)$$

Where η_{HHV} is the thermal efficiency based on HHV. N_{H_2} is the molar flow rate of hydrogen produced. Then, HHV is the higher heating value of hydrogen. Pel is the electrical power consumed by the electrolyzer. Using the values from the result we get that N_{H_2}=0.0029 mol/s, HHV=285.8 KJ/mol, and Pel 958.4W. We get that the higher heating values has a thermal efficiency of 86%. This means that 86% of electrical power entering the electrolyzer is converted into chemical energy of hydrogen.

The rest is dissipated as heat. The plot also shows that the thermal efficiency decreases as the current density increases, indicating that the losses increase with the current density.

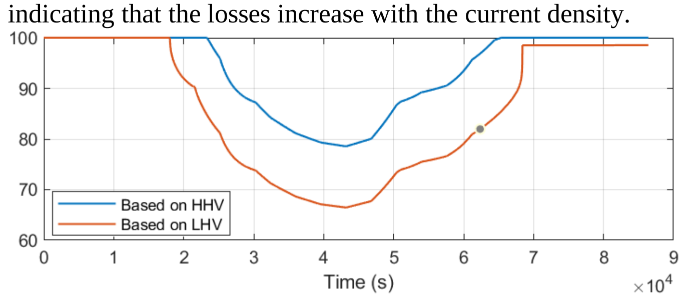

Fig. 8 Thermal Efficiency (%)

In Figure 9, the plot reveals the rates of hydrogen production, water consumption at the anode, and water transport to the cathode induced by diffusion, electro-osmosis drag, and hydraulic pressure differences. It also shows the equivalent energy based on its higher heating value. The higher heating value is the amount of energy released when hydrogen is burned, including the energy recovered by condensing the water vapor. The graph emphasizes the essential dehumidification step required to attain the desired purity of hydrogen. Notably, the production reaches its peak at approximately 0.2 g/s, providing a clear depiction of the dynamic processes governing the water and hydrogen flow within the PEM Electrolysis system.

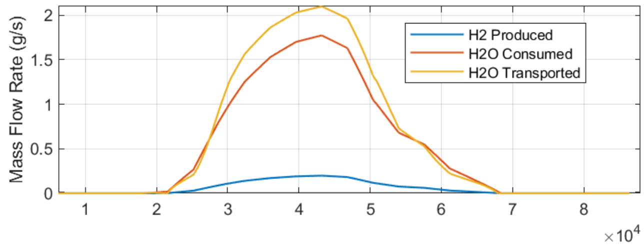

Fig. 9 Hydrogen and Water in MEA

Figure 10 The plot indicates that the mass of hydrogen produced, and the energy equivalent based on its HHV, which increases linearly with time, as the electrolyzer operates at a constant current density. The plot also shows that the mass of hydrogen produced reaches about 4.7 kg and the energy equivalent reaches about 180 kWh after a day of operation. The plot provides an indication of the amount of energy available if the hydrogen is used to generate power in a fuel cell.

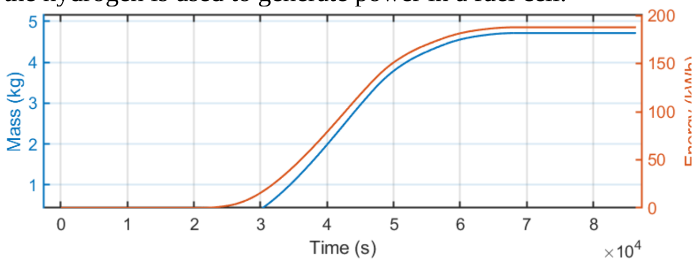

Fig. 10 Hydrogen produced

IV. Conclusions

These outcomes underscore the potential and feasibility of PEM electrolysis technology in tandem with renewable energy sources for green hydrogen generation, contributing to energy transition and sustainable development.

In the future, this technology holds promise for countries like Honduras, where it can be employed in cogeneration plants or fuel cells to generate electricity for homes, industries, hospitals, schools, and other public services. Green hydrogen emerges as a viable alternative to more expensive and polluting fossil fuels, enhancing energy security and resilience in the face of natural disasters affecting the electric grid. The integration of green hydrogen into various sectors positions it as a versatile and sustainable solution for the socio-economic and environmental challenges faced by developing nations like Honduras.

References

[1] A. Sayigh, «Up-date: Renewable energy and climate change», *Renew. Energy Environ. Sustain.*, vol. 6, p. 13, 2021.

[2] F. Sher, O. Curnick, y M. T. Azizan, «Sustainable Conversion of Renewable Energy Sources», *Sustainability*, vol. 13, n.º 5, Art. n.º 5, ene. 2021.

[3] H. A. Miller *et al.*, «Green hydrogen from anion exchange membrane water electrolysis: a review of recent developments in critical materials and operating conditions», *Sustain. Energy Fuels*, vol. 4, n.º 5, pp. 2114-2133, may 2020.

[4] J. L. Holechek, H. M. E. Geli, M. N. Sawalhah, y R. Valdez, «A Global Assessment: Can Renewable Energy Replace Fossil Fuels by 2050?», *Sustainability*, vol. 14, n.º 8, Art. n.º 8, ene. 2022.

[5] N. Naseri, S. El Hani, A. Aghmadi, H. Mediouni, I. Aboudrar, y M. Benbouzid, «Solar Photovoltaic Energy Storage as Hydrogen via PEM Fuel Cell for Later Conversion Back to Electricity», en *IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society*, oct. 2019, pp. 4549-4554.

[6] M. Paterson, «'The End of the Fossil Fuel Age'? Discourse Politics and Climate Change Political Economy», *New Polit. Econ.*, vol. 26, n.º 6, pp. 923-936, nov. 2021.

[7] H. Zakaria, M. Hamid, y E. M. Abdellatif, «Modelisation of Hydrogen Production using Photovoltaic Electrolysis», en *2019 Electric Vehicles International Conference (EV)*, oct. 2019, pp. 1-5.

[8]| M. J. Khan y M. T. Iqbal, «Dynamic modeling and simulation of a small wind–fuel cell hybrid energy system», *Renew. Energy*, vol. 30, n.º 3, pp. 421-439, mar. 2005.

[9] S. Boulmrharj, M. Bakhouya, K. Zine-dine, M. Siniti, y M. Khaidar, «Performance Analysis of a Grid-Connected PV Panels- Electrolyzer - Fuel Cell System for Cogeneration in Energy Efficient Buildings», en *2019 7th International Renewable and Sustainable Energy Conference (IRSEC)*, nov. 2019, pp. 1-5.

[10] M. L. Pierre, T. Abdelwahed, y R. Nabila, «Implementation of an Advanced PEM Hydrogen Storage System Based Cogeneration Using Photovoltaic System in a Building», en *2020 International Conference on Control, Automation and Diagnosis (ICCAD)*, oct. 2020, pp. 1-6.

[11] V. Liso, G. Savoia, S. S. Araya, G. Cinti, y S. K. Kær, «Modelling and Experimental Analysis of a Polymer Electrolyte Membrane Water Electrolysis Cell at Different Operating Temperatures», *Energies*, vol. 11, n.º 12, Art. n.º 12, dic. 2018.

[12] S. Dahbi, A. Aziz, N. Benazzi, y M. Elhafyani, «Optimised hydrogen production by a photovoltaic - Electrolysis system DC/DC converter and water-flow controller», en *2015 3rd International Renewable and Sustainable Energy Conference (IRSEC)*, dic. 2015, pp. 1-6.

[13] J. Mo *et al.*, «Thin liquid/gas diffusion layers for high-efficiency hydrogen production from water splitting», *Appl. Energy*, vol. 177, pp. 817-822, sep. 2016.

[14] F. Xue, J. Su, P. Li, y Y. Zhang, «Application of Proton Exchange Membrane Electrolysis of Water Hydrogen Production Technology in Power Plant», *IOP Conf. Ser. Earth Environ. Sci.*, vol. 631, n.º 1, p. 012079, ene. 2021.

[15] D. Guilbert y G. Vitale, «Experimental Validation of an Equivalent Dynamic Electrical Model for a Proton Exchange Membrane Electrolyzer», en *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, jun. 2018, pp. 1-6.