# Modeling and Simulation of a Renewable Energy PV/PEM with Green Hydrogen Storage

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## ABSTRACT

**The introduction of green hydrogen-based energy storage in association with renewable energy constitutes a promising and sustainable solution to the increase in energy demand while reducing greenhouse gas emissions. However, these hybrid systems face technical, economic, and logistic challenges that require a new transport and distribution architecture. The technical-economic study of these expensive installations requires good modeling and optimal sizing of the system components. This study presents a global model for hydrogen production and storage stations using photovoltaics (PV) and integrating Proton Exchange Membrane Fuel Cell (PEMFC) modules for electric vehicles. The simulations and sizing were based on the implementation of an effective mathematical model capable of accurately simulating the real dynamic behavior of the installation, the electrical and energy yields, the power consumed and produced, and finally the mass of hydrogen stored and/or consumed by the fuel cell. In this model, the hybrid system integrates PV solar panels with a maximum power of 1.2 MW, followed by a 1.0 MW Proton Exchange Membrane (PEM) electrolyzer, a high-pressure hydrogen storage tank, and a PEMFC to convert hydrogen into electricity. The simulation results showed that the energy generated by the PV panels can produce around 200 kg/day of green hydrogen by electrolysis, which makes it possible to power 100 electric cars per day with a range of 250 km for each.**

***Keywords-PV renewable energy; green hydrogen storage; fuel cell; PEM electrolyzer; energy efficiency; electrolysis***

## I. INTRODUCTION

In the 21st century, unprecedented energy challenges, such as reducing emissions, diversifying energy sources, and meeting the growing demand, highlight the importance of sustainable energy production systems. Solar photovoltaics (PV) and hydrogen, as cutting-edge technologies, are key pillars in the transition to a cleaner and more sustainable energy future. Many studies have investigated challenges and promising solutions in solar PV green energy and hydrogen production, highlighting the intermittent nature of PV power and the need for energy storage systems to minimize fluctuations. Some studies have identified current gaps and provide recommendations for more accurate and informative modeling to help analysts and policymakers improve the integration of renewable energy [1]. The aim is to ensure continuous and reliable hydrogen production. Many studies have focused on the modeling and simulation of such complex systems. This study aims to model and simulate a Proton Exchange Membrane (PEM) electrolyzer connected to a solar cell to better understand the factors affecting the production of hydrogen and oxygen. The difficulties include a precise model, temperature effects, and comparison with membrane-less electrolyzers. The results showed that PEM is suitable for hot, temperature-dependent desert regions and that an electrolyzer with a membrane produces much more hydrogen (2.25 l) than an electrolyzer without (0.0001 l) [2]. Hydrogen is considered a promising energy source, but it faces challenges such as dependence on fossil fuels, high production costs, and storage problems [3].

To meet these challenges, the development of cost-effective hydrogen production technologies, notably through renewable energy and improved supply chain efficiency, aims to make hydrogen a viable, sustainable, and economically efficient energy source. One approach to producing green hydrogen is to combine electrolysis with chemical methods, using materials such as perovskites to improve the electrolyzer performance. Using solar energy as a primary energy source can reduce hydrogen production costs by up to 7% compared to high-temperature electrolysis [4]. Hydrogen energy can be used in fuel cells of vehicles, but choosing between compressed hydrogen gas and liquid hydrogen for refueling requires energy considerations, with liquid hydrogen potentially consuming more [5]. The efficient integration of energy sources such as PV modules, fuel cells, and electrolyzers can help solve energy storage problems. By using solar energy to produce hydrogen through electrolysis, it is possible to stabilize and ensure a continuous energy supply [6]. Another example of an innovative solution involves optimizing the scale of a hybrid system integrating solar panels, fuel cells, and hydrogen storage to meet the energy needs of laboratories. Such a system can provide stable power with 96.7% renewable energy at a comparative cost, resulting in significant energy savings and a rapid return on investment [7]. Furthermore, the development of hybrid solar PV and hydrogen systems in grid-connected buildings improves renewable energy utilization, achieving high green energy supply levels and reducing $CO_2$ emissions through energy sector decarbonization [8]. The development of energy management and capacity sizing models for hybrid solar PV and hydrogen systems in grid-connected buildings represents a significant step forward. In [9], the obtained results showed that a 4.31 MW PV system combined with a 2.28 MW electrolyzer, a 500 KW fuel cell, and a 1.331 Kg hydrogen tank can supply most of the building's energy while reducing electricity imports from the grid equivalent to a reduction of 612,005.76 Kg $CO_2$ per year. When creating accurate models for hybrid renewable energy in grid-connected buildings, the solution lies in precise component dimensions and realistic system simulations. A study carried out in a building of a European university demonstrated that the model can accurately simulate a hybrid system, increasing solar energy consumption and reducing $CO_2$ emissions [10]. Complex simulations and modeling were used to evaluate the performance and efficiency of such systems, validating their feasibility and usefulness in real-world applications [11-17]. These innovative approaches are necessary to meet the challenges of hydrogen as an energy carrier and contribute to the transition to cleaner and more sustainable energy.

## II. MODELING GREEN STORAGE HYDROGEN

### A. Global Storage Architecture of Green Hydrogen

Solar hydrogen production and storage systems use solar energy to generate hydrogen by electrolysis, which is stored for later use. The system consists of several basic components, as shown in Figure 1. At first, 1.2 MW photovoltaic solar panels harness the energy of the sun to generate electricity. This electricity is then fed into a 1 MW PEM electrolyzer, which splits water into hydrogen and oxygen using the electricity generated by solar panels. The hydrogen produced is then stored in a specially designed high-pressure storage tank. The system contributes to the transition to clean, renewable energy by providing a sustainable energy storage solution that produces hydrogen from solar energy.

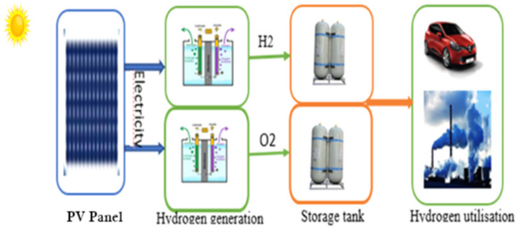

Fig. 1. Storage architecture of the green hydrogen system.

### B. Modeling of the Green Hydrogen System

The modeling and simulation process of the system comprises various components, such as PV panels, DC converters, hydrogen PEM electrolyzer, hydrogen storage tanks, and a PEM fuel cell, which are interconnected to construct the system model, as shown in Figure 2. The simulation was carried out using MATLAB, considering solar irradiation and ambient temperature. The mathematical models that represent the various components of the system were simulated using Simulink blocks, as shown in Figure 2.

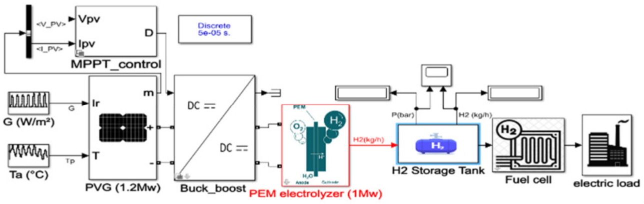

Fig. 2. Simulink model of the hydrogen production and storage system.

### C. Modeling of the PV Generator Equations

Mathematical models were used to evaluate the energy efficiency of PV cells, optimize the solar energy system, and evaluate its environmental impact. The output voltage of a PV cell is determined by the photocurrent, which is mainly influenced by the load current and the level of solar radiation during operation, as stated in [6, 17-21].

$$I_{PV} = N_P I_L - N_P I_S \left[ \exp\left( \frac{q\left(\frac{V_{PV}}{N_S} + \frac{I_{RS}}{N_P}\right)}{nkT} \right) - 1 \right] - \frac{\frac{N_S V_{PV}}{N_S}}{R_{sh}} \quad (1)$$

where $I_0$ is the PV cell reverse saturation current (A), $I_{PV}$ is the PV cell output current (A), $I_{sc}$ is the short-circuit cell current (A), $k$ is the Boltzmann's constant [j/K], $N_P$ is the number of parallel strings ($N_P$=78), $N_S$ is the number of series cells per string ($N_s$ =39), $q$ is the electron charge (C), $R_s$ is the series resistance of the PV cell (Ω), $T$ is the PV cell temperature (K), and $V_{PV}$ is the terminal voltage for the PV cell (V). The PV model available in the MATLAB software library was used and its parameters were adjusted to the specific needs of this study.

### *D. Modeling of the Converter*

DC-DC converters offer significant flexibility and high efficiency in controlling power in DC circuits. In the examined solar green hydrogen production system, a back-boost converter was used in combination with MPPT and P&O control. In this way, the PV system optimizes the production of solar energy to power the electrolyzer for hydrogen production, thereby contributing to the efficient and sustainable use of renewable energy. This system can also track the maximum power point under different irradiation and temperature conditions. The system of equations for a buck-boost converter in steady-state operation is provided in [22-23]:

$$\begin{pmatrix} \frac{dI_L}{dt} \\ \frac{dV_S}{dt} \\ \frac{dI_S}{dt} \end{pmatrix} = \begin{pmatrix} 0 & \frac{1-d}{L} & 0 \\ \frac{-1-d}{c} & 0 & \frac{-1}{c} \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} I_L \\ V_S \\ I_S \end{pmatrix} + \begin{pmatrix} \frac{d}{L} \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

where $V_{PV}$ and $V_S$ are the input and output voltages, $c$ is the capacitance of the dc-bus, $L$ is the value of the inductance, and $D$ represents the control signal of the switches.

### *E. Modeling the Hydrogen PEM Electrolyzer*

The Proton Exchange Membrane (PEM) electrolyzer is considered a viable alternative for hydrogen production from Renewable Energy Sources (RES). Many PEM fuel cell models have been reported, but few PEM electrolyzer models [17, 24-25]. Recently, the modeling of PEM electrolyzers has attracted growing interest from industry and researchers to optimize, design, and appropriately use PEM electrolyzers. The parameters used to model the electrolyzer are: $I_{el}$ and $V_{El}$ is the current and the voltage of the electrolyzer (A, V), respectively, $P_{El}$ is the power (KW), and $\eta_F$ is the Faraday efficiency [26]:

$$\eta_F = 96.5 e^{\left( \frac{0.09}{I_{El}} - \frac{75.5}{I_{El}^2} \right)} \tag{3}$$

$$V_{El}(t) = V_{in} + V_{anode}(t) + V_{cathode}(t) + R_{el}(t) I_{El}(t) \tag{4}$$

$$I_{El}(t) = I_{anode1}(t) + I_{anode2}(t) = I_{cathode1}(t) + I_{cathode2}(t) \tag{5}$$

$$P_{El}(t) = I_{El}(t) \times V_{El}(t) \tag{6}$$

$V_{El}$ is the voltage of the PEM electrolyzer, and $V_{in}$, $V_{anode}(t)$, $V_{cathode}(t)$, $R_{el}(t)$, $I_{El}(t)$, $I_{anode1}(t)$, $I_{anode2}(t)$, $I_{cathode1}(t)$, $I_{cathode2}(t)$, are, respectively, the open circuit voltage, the voltage losses in the anodes and cathodes, the electrolytes ohmic resistance, the stack current, the currents in the resistive and capacitive anode branches, and the currents in the resistive and capacitive cathode branches. Modeling the hydrogen production from the electrolyzer using RES is needed to account for changes resulting from load variations. Large electrolyzers are made up of cells connected in series. An integrated power unit controls current density and gas generation. Standard voltages for large electrolyzer installations are typically 400 V, 600 V, or 11 KV, depending on the size. Faradic efficiency is used to accurately quantify the hydrogen production of an electrolyzer, taking into account current losses due to gas diffusion. These losses affect the hydrogen production rate and vary with current. This is crucial, as the hourly variation in faradic efficiency is linked to the amount of hydrogen produced. The total hydrogen produced by an electrolyzer consisting of multiple stacks can be accordingly identified based on the number of operational stacks based on the law of ideal gases:

$$V_{H2}(t) = \eta_F(t) \frac{n_c I_{El}(t)}{2F} \tag{7}$$

The quantity of hydrogen produced by an electrolyzer consisting of several cells can be determined correspondingly by the operating number of cells, as shown in (8).

$$m_{H2prod}(t) = V_{H2} \times M \times n_c(t) \times 3600 \tag{8}$$

where $n_c$ is the number of cells within the electrolyzer, $I_{el}$ is the current applied to a single cell of the electrolyzer, the Faraday constant $F$ is 96485.33 C/mol, $T$ is the operating temperature of the electrolyzer (K), $m_{H2prd}(t)$ is the hourly mass of total hydrogen production by the electrolyzer unit (kg/h), $\eta_F(t)$ is the Faraday efficiency at the value of current absorbed by the electrolytic cell, and $M$ is the molar mass of the hydrogen gas ($2.016 \times 10^{-3}$ kg/mol). The model of the PEM electrolyzer was simulated in MATLAB/Simulink, as shown in Figure 3.

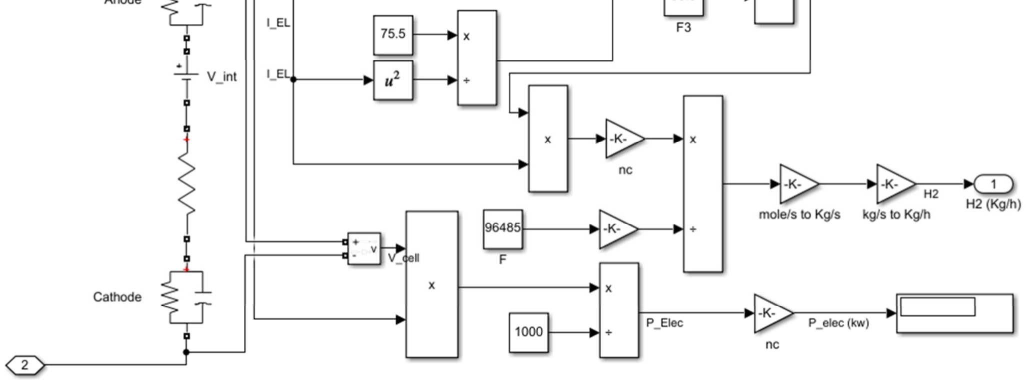

Fig. 3. Simulink model of the PEM electrolyzer.

### F. Modeling of the Hydrogen Storage Tank

The modeling of a hydrogen storage tank is essential for evaluating the performance of a hydrogen storage system. Gas equations of state, such as the ideal gas equation or the Van der Waals equation, are used to accurately simulate the behavior of the hydrogen inside the tank. The flow rate of the hydrogen is calculated at the operating pressure by:

$$P = z\frac{m_{H2}RT_{Tank}}{M\,V_{Tank}} + P_{initial} \qquad (9)$$

where $P$ is the gas pressure in pascals (Pa), $m_{H2}$ is the mass quantity of hydrogen, $R$ is the gas constant equal to 8.314 J/K·mol, $T_{tank}$ is the absolute temperature of the gas (K), $V_{tank}$ is the gas volume (m$^3$), and $z$ is the compressibility factor [17, 27]. The size of the hydrogen storage tank is determined by the amount of hydrogen consumed by the fuel cell. The system uses a hydrogen-based fuel that is charged during sunny hours and discharged at night to meet needs. The mass of hydrogen available in the storage tank at the time step in question is:

$$m_{tank}(t) = m_{init} + \int (H_{2in} - dm_{out})\ (t) \qquad (10)$$

where $m_{tank}(t)$ is the hydrogen mass available in the storage tank at time step $t$ (kg/h), $m_{init}(t)$ is the hydrogen storage tank hourly mass status, $H_{2in}$ is the mass of hydrogen product (kg/h), $dm_{out}$ is the mass of hydrogen consumed by the fuel cells. The hydrogen storage tank is shown in Figure 4.

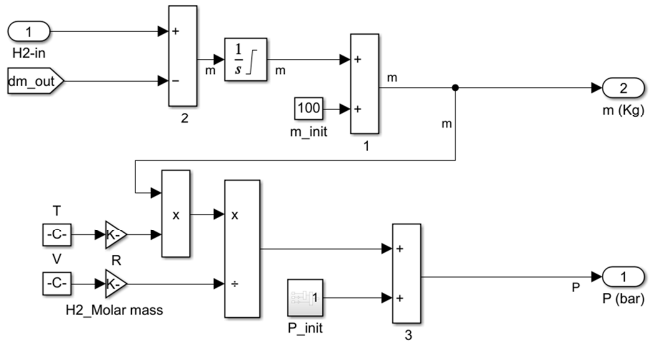

Fig. 4. Simulink model of the hydrogen storage tank.

### G. Modeling of the PEM Fuel Cell

In the PEM fuel cell, a solid polymer membrane is used as the electrolyte, allowing electrons to move around while limiting protons. This forces electrons to travel outside the membrane, generating an electric current that can be used later. The PEM fuel cell is known for its high energy efficiency, minimal pollutant emissions, reduced dependence on fossil fuels, and low greenhouse gas emissions. The flaw rate hydrogen consumption by a stack PEM fuel cell is given by:

$$dm_{out}(t) = \frac{P_{FC}(t)}{PCI * \eta_{FC}} \qquad (11)$$

where $dm(t)$ is the hydrogen mass consumption of the fuel cell (kg/h), $P_{fc}$ is the power of the PEM fuel cell system, $PCI$ is the lower hydrogen calorific value, and $\eta_{fc}$ is the efficiency of the fuel cell. The fuel cell was simulated in MATLAB/Simulink as shown in Figure 5.

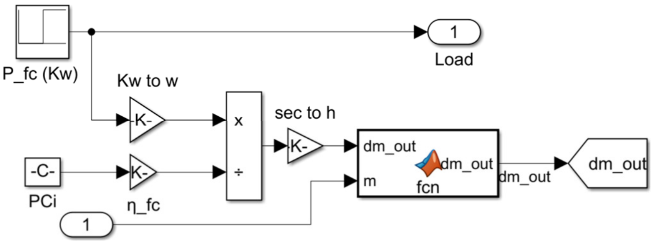

Fig. 5. Simulink model of the fuel cell.

## III. SIMULATION RESULTS AND DISCUSSION

The green hydrogen production and storage system uses PV solar energy to produce hydrogen through water electrolysis. The hydrogen produced is stored in a tank for later use [28]. This system offers a long-term renewable energy storage solution that can be used when solar energy is not available, such as during nighttime or cloudy days.

### A. Characteristics of the PV Panel

The green hydrogen production and storage system includes a 1.2 MW PV capacity in conjunction with a 1MW PEM electrolyzer unit, a 500 KW PEM fuel cell system, and a 350 Kg pressurized hydrogen storage tank, as illustrated in Table I.

TABLE I. PARAMETERS OF THE PROPOSED PV SYSTEM

| Parameters | Value/type |
|---|---|
| Total PV installed capacity | 1200 kW |
| Total number of PV modules | 3042 |
| Total Area requirement | 7.560 km² |
| PV Modules connection | 78 strings×39 in series |
| nominal power of each PV Module | 400 W |
| short-circuit current ($I_{sc}$) | 7.66 A |
| Open-circuit voltage ($V_{oc}$) | 48.5 V |

TABLE II. COMPONENTS OF THE HYDROGEN SYSTEM

| Components | PV Solar | Electrolyser | Storage tank | PEMFC |
|---|---|---|---|---|
| Capacity | 1.2 MW | 1MW | 800Kg | 500KW |

### B. Simulation Results

Simulations were carried out using MATLAB/Simulink, integrating real data from June 2020, including solar irradiation and ambient temperature. Tables I and II show the parameters used to develop the models for the PEM electrolyzer, hydrogen storage, and PEM fuel cell system, which were inspired from [9]. Figure 6 represents the daily load power request, and Figures 7 and 8 illustrate the ambient temperature and PV power outputs. Figures 8 and 9 show the hourly hydrogen production rate by the PEM electrolyzer. It can be concluded that the selected electrolyzer operates at variable power levels in response to intermittent solar energy generation to store excess PV energy in the form of green hydrogen during hours of excess solar energy production and the mass of hydrogen consumed by the fuel cell. Figure 10 shows the hourly mass of hydrogen stored, with a maximum value of up to 250 Kg. Figure 11 represents the simulation results of $H_2$ production as a function of electrical current. As the current supply to the electrolyzer increases, the bond-breaking dissociation reaction of the water molecules increases rapidly. The simulation results were compared with those of [29].

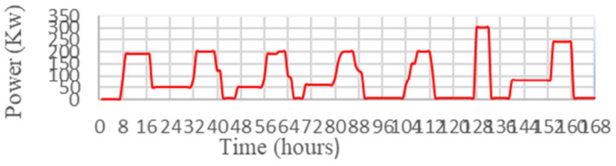

Fig. 6. Load demand (kW).

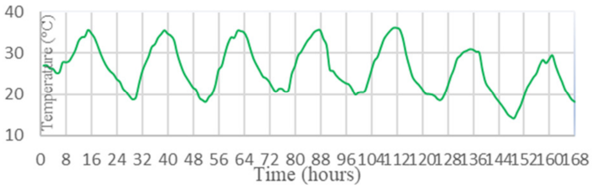

Fig. 7. Hourly ambient temperature.

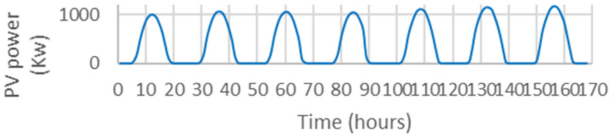

Fig. 8. Hourly PV power generation.

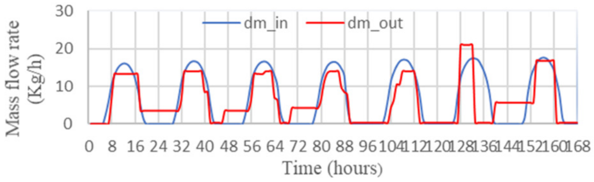

Fig. 9. The mass flow rate of hydrogen production and the mass of hydrogen consumed by the fuel cell (dm_out).

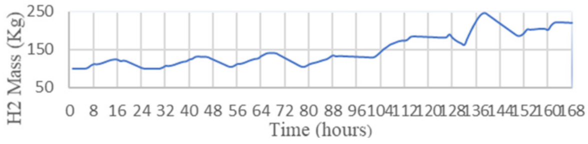

Fig. 10. The stored hydrogen masses.

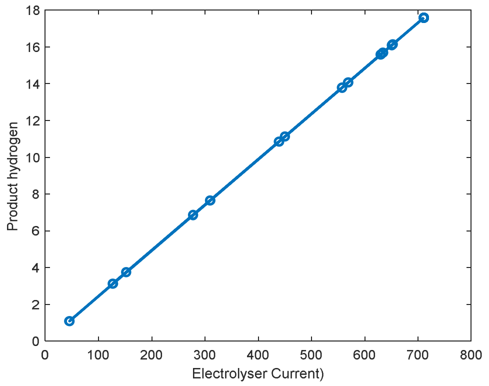

Fig. 11. $H_2$ production as a function of current.

### *C. Discussion*

To evaluate the performance of the developed model in terms of real-world production, the simulation results shown in Figures 7 to 12 were compared with those of [10], considering the electrochemical losses occurring in the PEM electrolyzer and the PEM fuel cells. According to the simulations of the hydrogen levels in the hydrogen tank, the maximum level reached in the hydrogen tank was 250 kg of hydrogen with the proposed model, compared to approximately 86.5 kg in [10]. This highlights the potential benefits of the proposed model for more accurately determining the capacity of hydrogen storage systems, thus avoiding the possibility of oversizing associated with additional costs and space requirements. Furthermore, it confirms that the accumulated hydrogen volume never exceeds the maximum recommended storage capacity of the hydrogen tank. The corresponding operating pressure achieved at this time was around 350 bar, confirming the recommended pressure for the hydrogen tank.

## IV. CONCLUSION

Green hydrogen production and storage systems constitute a very viable option to meet the needs of various areas (industries, transport, storage, buildings, etc.) and contribute to an economy with low greenhouse gas emissions. In this context, this study developed a global model of a hydrogen production and storage station using PVs and integrating a PAC module to power electric vehicles for sustainable development and the protection of the ecosystem. A mathematical model was developed to evaluate the station's performance and optimize its operation and production. Storage efficiency and volume increased by approximately 30% under real climate conditions and dynamic PV behavior. This is very important to support sustainable transport and the green industry in the context of renewable energy integration, ensuring a sustainable energy transition.

## REFERENCES

[1] J. Bistline, G. Blanford, T. Mai, and J. Merrick, "Modeling variable renewable energy and storage in the power sector," *Energy Policy*, vol. 156, Sep. 2021, Art. no. 112424, https://doi.org/10.1016/j.enpol.2021.112424.

[2] B. Mohamed, B. Alli, and B. Ahmed, "Using the hydrogen for sustainable energy storage: Designs, modeling, identification and simulation membrane behavior in PEM system electrolyser," *Journal of Energy Storage*, vol. 7, pp. 270–285, Aug. 2016, https://doi.org/10.1016/j.est.2016.06.006.

[3] Z. Abdin, A. Zafaranloo, A. Rafiee, W. Mérida, W. Lipiński, and K. R. Khalilpour, "Hydrogen as an energy vector," *Renewable and Sustainable Energy Reviews*, vol. 120, Mar. 2020, Art. no. 109620, https://doi.org/10.1016/j.rser.2019.109620.

[4] M. Pein, N. C. Neumann, L. J. Venstrom, J. Vieten, M. Roeb, and C. Sattler, "Two-step thermochemical electrolysis: An approach for green hydrogen production," *International Journal of Hydrogen Energy*, vol. 46, no. 49, pp. 24909–24918, Jul. 2021, https://doi.org/10.1016/j.ijhydene.2021.05.036.

[5] A. Bauer, T. Mayer, M. Semmel, M. A. Guerrero Morales, and J. Wind, "Energetic evaluation of hydrogen refueling stations with liquid or gaseous stored hydrogen," *International Journal of Hydrogen Energy*, vol. 44, no. 13, pp. 6795–6812, Mar. 2019, https://doi.org/10.1016/j.ijhydene.2019.01.087.

[6] T. Lajnef, S. Abid, and A. Ammous, "Modeling, Control, and Simulation of a Solar Hydrogen/Fuel Cell Hybrid Energy System for Grid-Connected Applications," *Advances in Power Electronics*, vol. 2013, Apr. 2013, Art. no. 352765, https://doi.org/10.1155/2013/352765.

[7] M. S. Okundamiya, "Size optimization of a hybrid photovoltaic/fuel cell grid connected power system including hydrogen storage," *International*

*Journal of Hydrogen Energy*, vol. 46, no. 59, pp. 30539–30546, Aug. 2021, https://doi.org/10.1016/j.ijhydene.2020.11.185.

[8] J. Li, G. Li, S. Ma, Z. Liang, Y. Li, and W. Zeng, "Modeling and Simulation of Hydrogen Energy Storage System for Power-to-gas and Gas-to-power Systems," *Journal of Modern Power Systems and Clean Energy*, vol. 11, no. 3, pp. 885–895, Feb. 2023, https://doi.org/10.35833/MPCE.2021.000705.

[9] A. I. Atteya, D. Ali, and M. Hossain, "Developing an effective capacity sizing and energy management model for integrated hybrid photovoltaic-hydrogen energy systems within grid-connected buildings," pp. 204–212, Jan. 2022, https://doi.org/10.1049/icp.2022.1823.

[10] A. I. Atteya, D. Ali, and N. Sellami, "Precise Dynamic Modelling of Real-World Hybrid Solar-Hydrogen Energy Systems for Grid-Connected Buildings," *Energies*, vol. 16, no. 14, Jan. 2023, Art. no. 5449, https://doi.org/10.3390/en16145449.

[11] L. Stoyanov, "Modeling of Hybrid System with Photovoltaic Panels-Fuel cells Generation and Hydrogen Storage Using Electrolyzer," in *2021 17th Conference on Electrical Machines, Drives and Power Systems (ELMA)*, Sofia, Bulgaria, Jul. 2021, pp. 1–4, https://doi.org/10.1109/ELMA52514.2021.9502964.

[12] M. Djilali, "Contribution à la conception de la chaîne logistique de l'hydrogène," Ph.D. dissertation, Université Kasdi Merbah Ouargla, 2021.

[13] N. A. El-Taweel, H. Khani, and H. E. Z. Farag, "Hydrogen Storage Optimal Scheduling for Fuel Supply and Capacity-Based Demand Response Program Under Dynamic Hydrogen Pricing," *IEEE Transactions on Smart Grid*, vol. 10, no. 4, pp. 4531–4542, Jul. 2019, https://doi.org/10.1109/TSG.2018.2863247.

[14] H. Charane, "Gestion Intelligente d'un système à pile à combustible," MSc Thesis, Universite Blida, Algeria, 2016.

[15] Y. Cao and T. Parikhani, "A solar-driven lumped SOFC/SOEC system for electricity and hydrogen production: 3E analyses and a comparison of different multi-objective optimization algorithms," *Journal of Cleaner Production*, vol. 271, Oct. 2020, Art. no. 122457, https://doi.org/10.1016/j.jclepro.2020.122457.

[16] B. Han, S. M. Steen, J. Mo, and F.-Y. Zhang, "Electrochemical performance modeling of a proton exchange membrane electrolyzer cell for hydrogen energy," *International Journal of Hydrogen Energy*, vol. 40, no. 22, pp. 7006–7016, Jun. 2015, https://doi.org/10.1016/j.ijhydene.2015.03.164.

[17] S. Boulmrharj, M. Khaidar, M. Bakhouya, R. Ouladsine, M. Siniti, and K. Zine-dine, "Performance Assessment of a Hybrid System with Hydrogen Storage and Fuel Cell for Cogeneration in Buildings," *Sustainability*, vol. 12, no. 12, Jan. 2020, Art. no. 4832, https://doi.org/10.3390/su12124832.

[18] K. Njeh, M. A. Zdiri, M. B. Ammar, A. Rabhi, and F. B. Salem, "Energy Management of an Autonomous Photovoltaic System under Climatic Variations," *Engineering, Technology & Applied Science Research*, vol. 13, no. 1, pp. 9849–9854, Feb. 2023, https://doi.org/10.48084/etasr.5375.

[19] M. Elibrahimi, A. Elmouatamid, M. Bakhouya, K. Feddi, and R. Ouladsine, "Performance Evaluation of Fixed and Sun Tracking Photovoltaic Systems," in *2018 6th International Renewable and Sustainable Energy Conference (IRSEC)*, Rabat, Morocco, Sep. 2018, pp. 1–6, https://doi.org/10.1109/IRSEC.2018.8702932.

[20] S. Boulmrharj *et al.*, "Modeling and Dimensioning of Grid-Connected Photovoltaic Systems," in *2017 International Renewable and Sustainable Energy Conference (IRSEC)*, Tangier, Morocco, Sep. 2017, pp. 1–6, https://doi.org/10.1109/IRSEC.2017.8477392.

[21] I. Benabdallah and A. Cherif, "Improved Modeling and Control of a HTA Grid Connected 500 KW PV Systems," *Indian Journal of Science and Technology*, vol. 10, no. 27, pp. 1–11, Jun. 2017, https://doi.org/10.17485/ijst/2017/v10i27/116134.

[22] R. Marouani, M. A. Sellami, and A. Mami, "Photovoltaic water pumping system controlled by cascade sliding mode.," *Research Journal of Applied Sciences, Engineering and Technology*, vol. 7, no. 20, pp. 4364–4369, 2014.

[23] R. Marouani, K. Echaieb, and A. Mami, "New Alternative of Design and Control for Three-Phase Grid-Connected Photovoltaic System," *European Journal of Scientific Research*, vol. 55, no. 1, pp. 37–45, 2011.

[24] D. A. Llerena Cordova, "Sizing of solar-based hydrogen production systems in North Africa and transportation of hydrogen-natural gas blend to Italy," MSc Thesis, Politecnico di Torino, Italy, 2019.

[25] B. E. Boya Bi, P. Gbaha, M. P. E. Koffi, and K. B. Koua, "Modélisation Des Composants D'un Système Hybride Panneaux Photovoltaïque – Stockage D'énergie Via L'hydrogène – Batteries," *European Scientific Journal, ESJ*, vol. 14, no. 3, Jan. 2018, https://doi.org/10.19044/esj.2018.v14n3p545.

[26] G. De Lorenzo, R. G. Agostino, and P. Fragiacomo, "Dynamic Electric Simulation Model of a Proton Exchange Membrane Electrolyzer System for Hydrogen Production," *Energies*, vol. 15, no. 17, Jan. 2022, Art. no. 6437, https://doi.org/10.3390/en15176437.

[27] T. Yigit and O. F. Selamet, "Mathematical modeling and dynamic Simulink simulation of high-pressure PEM electrolyzer system," *International Journal of Hydrogen Energy*, vol. 41, no. 32, pp. 13901–13914, Aug. 2016, https://doi.org/10.1016/j.ijhydene.2016.06.022.

[28] M. A. Aminudin, S. K. Kamarudin, B. H. Lim, E. H. Majilan, M. S. Masdar, and N. Shaari, "An overview: Current progress on hydrogen fuel cell vehicles," *International Journal of Hydrogen Energy*, vol. 48, no. 11, pp. 4371–4388, Feb. 2023, https://doi.org/10.1016/j.ijhydene.2022.10.156.

[29] A. S. Tijani, N. A. B. Yusup, and A. H. A. Rahim, "Mathematical Modelling and Simulation Analysis of Advanced Alkaline Electrolyzer System for Hydrogen Production," *Procedia Technology*, vol. 15, pp. 798–806, Jan. 2014, https://doi.org/10.1016/j.protcy.2014.09.053.