E3S Web of Conferences **675**, 01017 (2025) https://doi.org/10.1051/e3sconf/202567501017
GeoME'5.5 2025

Hybrid PV/PEM-EL-FC energy system for civil engineering applications: a review

Fatima Mokhliss[1*], *El Ayachi* Chater[1] and *Larbi* Chrifi-Alaoui[2]

[1]LASTIMI Lab, EST Salé, Mohammed V University in Rabat, Morocco
[2]LTI Lab, University of Picardie Jules Verne in Amiens, France

Abstract. This study focuses on the landscape, control methodologies, and extendability of hybrid energy systems that include photovoltaic power generation, hydrogen generated from renewable energy via proton exchange membrane-based electrolyzers, and fuel cells. It also highlights the ability of energy systems to be used in various aspects of civil engineering, especially when there are limited or unreliable of energy. Hybrid energy systems offer the capability of providing sustainable, and dependable sources of energy; therefore, they can contribute to the development of self-sufficient infrastructure in areas lacking sustainable sources of energy. Ultimately, this review indicates that an increasing number of articles on the use of fuzzy logic based maximum power point tracking algorithms, which are designed to optimize the performance of photovoltaic systems in real time environments, are being written. Also, recent publications on PV/PEM-EL-FC hybrid systems have demonstrated the feasibility of addressing the intermittent nature of solar power generation. The pursuit of reliable energy independence, and sustainable greenhouse gas emission reduction, has been linked to the transition to "green" through a myriad of interrelated issues. Therefore, this review identifies the gaps in existing research, relevant technological challenges, and possible opportunities for integrating this technology into the field in the future.

1 Introduction

Global concern for mitigating environmental effects of energy production and consumption and transitioning from fossil-based energy production has resulted in an interest in renewable energy options such as hydrogen energy [1] and green hydrogen. To address the increasing global energy demands in a manner that fosters sustainable social and economic growth; while promoting innovation, and supporting global economies it is expected that hydrogen energy will be widely used throughout many different sectors (transportation/mobility, micro-grids, residential etc.) as a means to meet energy demands. Hybrid energy systems consisting of at least two different energy production methods, are known to provide improved power quality, flexibility, and reliability [2]. Therefore, providing a combination of PV (Photovoltaic Systems) and PEM (Proton Exchange Membrane) Fuel Cells, provides a potential architectural structure to utilize the benefits of both types of energy production

* Corresponding author: mokhliss.fatima1@gmail.com

systems. PV systems produce energy using sunlight, therefore they can generate clean energy by utilizing available solar irradiance during daylight hours [3], whereas, PEM Fuel Cells maintain a consistent, and dispatchable energy output, thereby providing a base load supply during all time periods (day and night), thus addressing the lack of PV energy generation when solar radiation is not present [4]. Another key component to these systems is the electrolyzer that uses excess energy generated by the photovoltaic system to produce hydrogen. These systems offer the benefit of storing energy as hydrogen for use in a fuel cell at later on. The combination of PV modules, electrolyzers, and fuel cells produces a sustainable and reliable green energy solution when combined with forms of energy storage such as batteries [5].

However, PV systems demonstrate an intrinsic rate of intermittency due to load demand variations, irradiance, and temperature variation. Variability in PV outputs and switching failures in power electronic equipment can lead to quality issues such as voltage stability changes, frequency variations, and increased harmonic distortion. To ensure that maximum energy is obtained from photovoltaic panels during time-varying conditions, as well as to maximize performance efficiency, maximum power point tracking (MPPT) algorithms are required. Traditional rule-based control systems usually do not have the necessary flexibility for highly dynamic situations, and with the increasing cumulative considerations of uncertainties and nonlinearities in hybrid renewable systems, the importance of intelligent rule-based control methods has increased exponentially.

In light of this potential for hybrid systems, as well as some of the issues outlined above, fuzzy logic control is being developed as a desirable method for MPPT, as well as other control systems that incorporate PV and hybrid PV-FC systems. FLC-based MPPT techniques can respond immediately to changes in the environmental state and are insensitive to circuit parameter changes, which can improve system reliability and stability through less oscillation and faster response time than other traditional methods [6].

The use of these hybrid PV-Electrolyzer-Fuel Cell systems with intelligent control is highly relevant to civil engineering applications. Hybrid systems can supply clean and reliable power for a multitude of uses in built environments. These applications can take the form of autonomous buildings and communities, decentralized energy infrastructure or microgrids where the energy is produced near the end-user, or applications where electricity would be supplied to remote and/or isolated locations where grid power is difficult and/or costly to supply. Potential applications can also include powering charging stations (which can be a critical infrastructure in civil engineering developments) or loading energy at isolated construction sites and/or remote fixed locations far from the grid electricity supply.

This paper will review hybrid PV-Electrolyzer-Fuel Cell systems while focusing on the FLC techniques used in MPPT algorithms. It will consider their current and potential applications in the civil engineering field.

2 PV/PEM-EL-FC System Technologies and Components

A hybrid system combining photovoltaic panels (PV), a proton exchange membrane electrolyzer (PEM-EL), hydrogen storage, and a proton exchange membrane fuel cell (PEM-FC) is based on the integration of several key technologies to produce and manage energy in an independent, environmentally friendly way [7].

2.1 Photovoltaic technology

PV convert solar energy into direct current electricity (DC). This process, known as the PV effect, is achieved by illumination of junctions between two different materials by photons, thereby generating an electrical potential.

There are several types of PV cells, usually polycrystalline Si (poly-Si) or monocrystalline Si (mono-Si). Mono-Si cells type are known for their exceptional conversion efficiency, whereas poly-Si is often more cost-effective [8]. Comparative studies, notably in Morocco, have shown favorable performance for polycrystalline and monocrystalline silicon-based systems. The panel efficiency is affected by irradiance and ambient temperature [9].

2.2 Electrolyzer

By the process of water electrolysis [10] the electrolyser converts electrical energy and water H_2O into hydrogen H_2 and oxygen O_2. This electrochemical process is the division of water (H_2O) into components in the gas phase [11].

In the hybrid systems studied, the use of the PEM-EL (proton exchange membrane electrolyser) is common. There are many important features such as: compact form; rapid reaction of the system; very dynamic operation; very efficient and producing a high purity of hydrogen. Its rapid reaction indicates its suitability for use with a variable supply of renewable energy such as solar and wind power. The overall reaction occurring in water electrolysis is represented as follows:

$$2H_2O + \text{Electrical energy} + \text{Heat} \rightarrow 2H_2 + O_2 \quad (1)$$

In comparison, other electrolyser technologies of electrolyser are:

Alkaline (AEL): This technology is more widely used than any other electrolyser technology, with the longest history of application and cost-effectiveness. However, it is poorly suited to power supply variations and exhibits low kinetics in both mass transport and electrochemistry [9].

Solid Oxide (SOEC): This technology is offered as promising in that higher efficiencies can be gained. It works at high temperatures (600° to 1000°C). Stability is apt to be a more serious problem, as it is with SOFC [1].

2.3 Hydrogen storage

The hydrogen produced by the electrolyzer must be stored for later use by the fuel cell, particularly during periods of low ENR production [1]. The most commonly mentioned storage method is compressed gas storage in high-pressure tanks (e.g. 350 bar [7], 120 bar, and 70 bar [5]). This compression increases the density of hydrogen and reduces its storage volume [1].

Other storage options include liquefaction or solid-state storage, for example, in metal hydrides. Hydrogen storage is essential for guaranteeing the safety and autonomy of off-grid systems, particularly in isolated areas [7]. It is suitable for both long-term and seasonal storage [1].

2.4 Fuel Cells

Fuel cells are electrochemical devices that use oxygen (typically from air and supplied at the cathode) and hydrogen (provided at the anode) to produce energy.

They convert chemical energy into electrical energy and produce heat and water as by-products.

The PEM-FC is particularly well suited to micro-cogeneration applications (combined heat and power - CHP). Its many advantages include rapid start-up, ability to follow load variations, high power density, low operating temperature (generally below 100°C, around 80°C) [1], reduced corrosion, and high efficiency (reaching up to 85-90% in CHP systems according to some sources, although an efficiency of 50% is sometimes considered in simulations) [3]. PEM-FCs have no direct emissions, producing only water, making them an environmentally friendly choice.

The overall reaction is:

https://doi.org/10.1051/e3sconf/202567501017

$$O_2 + 2H_2 \rightarrow 2H_2O + Heat + Electricity \qquad (2)$$

Comparison with other types:

SOFC (Solid Oxide Fuel Cell): Highly efficient, they operate at very high temperatures (600-1000°C) and can use a variety of fuels [1]. They can be integrated into micro-turbines or thermo-photovoltaic systems for multi-generation applications [5].

Other types exist and are categorized as solid polymer fuel cells (SPFCs), direct methanol fuel cells (DMFCs), phosphoric acid fuel cells (PAFCs), and alkaline fuel cells (AFCs) based on the electrolyte, operating temperature, and fuel [1].

2.5 Hydrogen typology

Hydrogen can be classified according to its production method.

2.5.1 Green Hydrogen

Produced through employing power from renewable energy sources (RES) to electrolyze water. This sustainable, low-carbon method is receiving increasing attention in energy research. It is considered to have almost zero emissions during production [5]. The emphasis in PV/PEM-EL-FC hybrid systems is on green hydrogen production.

2.5.2 Grey Hydrogen

Mostly produced from fossil feedstocks, mainly by steam reforming of natural gas [11]. This process generates significant CO_2 emissions (nearly 12 tons of CO_2 per ton of H_2). In the context of green hybrid systems, this is useless [5].

2.5.3 Blue Hydrogen

It is produced using fossil fuels as well, but carbon capture and storage (CCS) is also used technologies to reduce CO_2 emissions. Although less emitting than grey hydrogen, it is still based on fossil sources and is not the focus of fully renewable hybrid systems.

3 Hybrid system architecture and configuration

The architecture of a PV/PEM-EL-FC hybrid system is designed to optimize the flow of energy between separate components, exploiting the intermittency of renewable sources to provide a reliable, continuous power supply.

3.1 Functional Overview

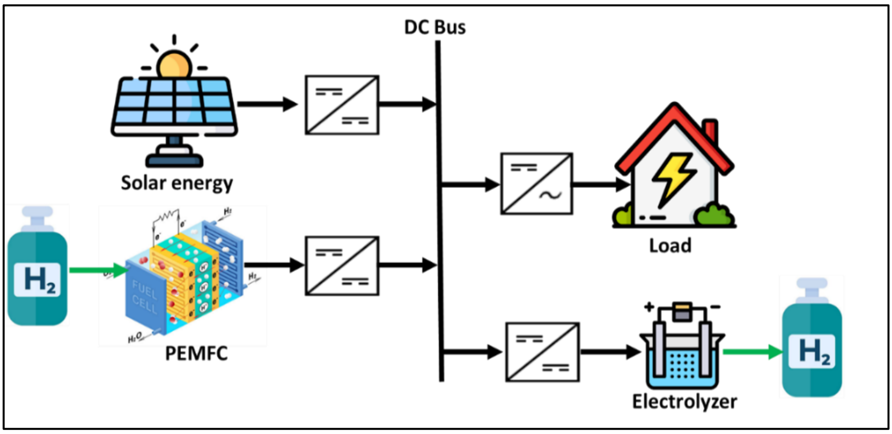

Fig. 1. Hybrid PV/PEM-EL-FC system architecture.

The typical energy chain of such a hybrid system is as follows: solar energy is captured by PV panels, optimized via a maximum power point controller (MPPT), and converted into DC electricity. This electricity can then be used directly to power the load. Excess electricity that is not consumed by the load and/or used to charge the batteries (if present) is directed to the electrolyzer. The electrolyzer uses this electricity to produce hydrogen from water [10]. The hydrogen thus generated was stored in dedicated tanks. When PV production is insufficient (at night, on overcast days, etc.), the stored hydrogen feeds the fuel cell, which converts it back into DC or AC electricity to supply the load [1], as presented in Fig. 1.

3.2 Conditioning and Power Control

The capacity of renewable energy generation devices, such fuel cells (FC) or photovoltaic (PV) panels, to function at their maximum power point (MPP) under various load or environmental circumstances is crucial to their effective operation. Maximum Power Point Tracking (MPPT) algorithms must be used in order to accomplish this objective. MPPT generally controls the duty cycle of a DC/DC converter (often a boost converter for PV), as presented in Fig. 2.

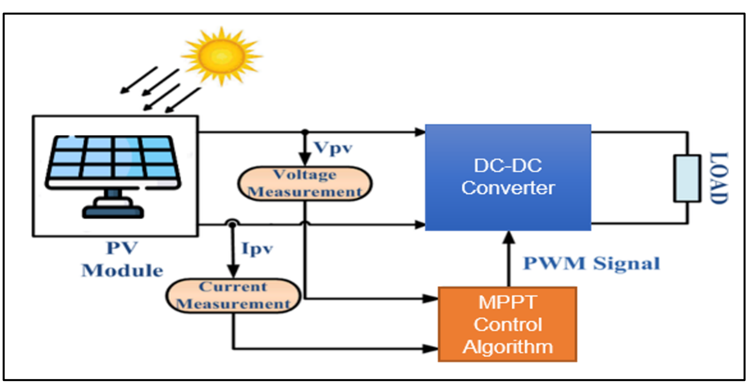

Fig. 2. Schematic to control a PV using the MPPT technique.

Different algorithms are used for MPP tracking, including Incremental Conductance (INC) and Perturb & Observe (P&O). Fuzzy logic controllers (FLC) are also applied to MPPT, which is why several studies have compared the performance of FLC-based MPPT methods with other techniques.

FLC and conventional methods (P&O, INC): FLC shows significant advantages over P&O and INC because it reduces oscillations in the steady state and has a shorter tracking time. For example, a PV system based on FLC showed a prompt response with almost eliminated transients and no marked oscillations during irradiance changes, converting over 99% of the power, whereas INC presented high transient and marked oscillations, converting around 80% [12].

FLC and other intelligent controllers (ANN, PSO): In the context of PV-FC hybrid DC microgrids, a comparative study between FLC, ANN, and PSO showed that the fuzzy MPPT method offers increased MPP tracking capability and reduced oscillations in the steady state [6]. The FLC was the fastest to reach the MPP, with a settling time of 0.035 s, compared with 0.054 s for the ANN and 0.650 s for the PSO. Furthermore, FLC has demonstrated higher output power compared to ANN and PSO controllers in photovoltaic (PV) and fuel cell (FC) systems [6]. A subsequent study found that the fuzzy current controller, as opposed to the ANN-based controller for a PV-FC hybrid microgrid, exhibited improved power quality, with better performance in terms of voltage and frequency deviation, total harmonic distortion (THD), etc. [2].

4 Applications in Civil Engineering

4.1 Building Energy Supply

Hybrid PV-PEMFC are commonly considered as systems capable of generating electrical energy and potentially thermal energy to many types of buildings [1]. including:

Residential buildings: Providing power to small houses in general, primarily in stand-alone or off-grid situations; this will reduce dependency on batteries, and therefore can help extend the life cycle of the whole system. Research studies have proven that hybrid PV-PEMFC systems are very effective at providing valuable electricity and heat to buildings [1], Therefore they may be applicable for single-family homes and for multi-building complexes.

Commercial and Public Buildings: Hybrid PV-PEMFC microgrid systems can benefit commercial and public buildings such as hotels, universities, and schools [3]. For example, a study was performed to determine if a hybrid PV/PEMFC microgrid system could be applied to a university building to improve the efficiency of traditional power delivery to the building [4].

Community Power Systems: These systems may be able to generate power for community loads in villages and small communities, specifically in remote areas, and thus can contribute to rural electrification [3,13].

4.2 Water Management Systems

Solar energy is becoming an important factor in water management [8], and hybrid PV-PEMFC systems can generate energy for a variety of water-related civil infrastructure.

Desalination Plants: They can provide power to desalination plants, including reverse osmosis plants, in locations where there is a high amount of solar radiation [2]. Many studies have analyzed the technical and economic viability of using desalination units [4].

Water Pumping and Irrigation Systems: Hybrid systems can support irrigation water pump systems, particularly those located in remote rural areas, and serve as a sustainable alternative to diesel pumps [7]. An example of this application is the use of hybrid systems in vineyard pumping stations for irrigation systems [4].

Wastewater Treatment Plants: Integration of PV-Rhfc systems with wastewater treatment has also been studied [4].

4.3 Transportation Infrastructure

While the focus is generally on the transportation vehicle itself, the systems can also generate power for supporting sustainable transportation infrastructure.

Electric Vehicle (EV) Charging Stations: Hybrid PV-Fc systems, which are often coupled with battery storage, can be utilized for powering electric vehicle charging stations, particularly in retail parking areas or as part of smart city infrastructure [4].

Hydrogen Refueling Stations: Solar powered hydrogen refueling stations have been conceptualized and developed for smart city applications to enable local hydrogen generation.[4].

5 Discussion

In this section, the reviewed literature on hybrid PV/PEM-EL-FC systems is analyzed from a critical perspective, with an emphasis on their performance, techno-economic feasibility, and applicability potential in civil engineering infrastructure. The results are summarized below in the form of comparative tables and subsequently contextualized.

5.1 Techno-Economic Viability

To assess the economic feasibility of hybrid systems, numerous studies used optimization tools (e.g., HOMER Pro, ISABO, PSO) to calculate the levelized cost of energy (LCOE), net present cost (NPC), etc. [3,7,13], as shown in Table 1.

Table 1. Techno-Economic Performance Indicators.

Application	Configuration	NPC (USD)	LCOE (USD/kWh)	Key Findings
NEOM, Saudi Arabia (community) [13]	PV + FC + Battery	500,823	0.126	67.3% cheaper than diesel
Algeria (telecom tower) [3]	PV + EL + FC + Battery +H2 tank	64,384	0.259	Lowest CAPEX of 35 850 $
NEOM (desalination plant) [14]	PV + EL + FC + Battery	438,657	0.117	Effective for industrial use
Generic (multi-objective optimization) [15]	PV + Wind + FC	-	-	12% reduction in NPC and LCOE using ISABO

The results indicate a favorable trend: hybrid systems are rapidly approaching the cost of traditional solutions, especially in off-grid or remote settings. Green hydrogen is decreasing in price from \$40/kg in 2008 to \$3.4/kg in 2022 and thus increasing the financial attractiveness of PV/H2 systems. However, the initial investment required for the installation of hybrid systems is still a major barrier, especially for developing countries or for small scale implementations.

5.2 Environmental Impact and Sustainability

The integration of hydrogen based on PEM technology provides for considerable reduction of greenhouse gas emissions, especially when compared to fossil fuel based backup generators. For example, in NEOM, the annual CO_2 emissions were decreased by approximately 133,047 kg [13]. In addition, PV noise barriers (PVNBs) have shown both energy and environmental co-benefits and demonstrate that hybrid systems can contribute not only to energy security but also to urban sustainability [8]. Nevertheless, the positive environmental impact of hybrid systems is subject to the quality of the raw material used and the lifecycle impacts of PEM technologies. Future research should prioritize the assessment of the environmental payback period of hybrid systems via Life Cycle Assessment (LCA).

5.3 Challenges and Limitations

Despite the promising results, several challenges remain and are highlighted in Table 2. Therefore, addressing these challenges requires a combination of technical and social science/policy approaches. Short-term technical priorities are mass production to lower costs, improving the durability and lifetimes of components and standardizing control architectures. Simultaneously, long-term social science and policy research priorities include increasing user acceptance, identifying training requirements and establishing regulatory frameworks.

Table 2. Main Barriers Identified in the Literature.

Barrier	Description	Implications
High CAPEX	Electrolyzers and FCs are still expensive	Limits adoption in low-resource contexts
Durability Concerns	PEM components may degrade over time	Affects system reliability and lifespan
Control Complexity	Coordinating hybrid energy sources is challenging	Requires advanced, real-time control
Model Limitations	Oversimplified assumptions in simulations	Reduced accuracy in real-world applications
Data Gaps	Site-specific and market data often missing	Hinders generalized conclusions
Public Acceptance	Lack of familiarity with H_2 infrastructure	Potential social resistance

5.4 Researcher's Perspective

The literature strongly supports the technical readiness and viability of hybrid PV/PEM-EL-FC systems for civil engineering application. Although energy performance parameters and environmental credentials can make a strong case for practical viability, their realization will ultimately require cost-effective, scalable integration strategies and firm control strategies. We are aware that the interaction of PV and hydrogen works as a potentially viable approach to decentralized, low-emission energy systems. However, to support and scale laboratory potentials to actual operational realities, rigorous hardware-in-the-loop validations, multi-domain co-simulations, and inter-sector deployment studies are necessary. We believe that focusing on energy management systems, lifespan issues, and thermal energy reuse issues are important focuses even though they have not been explored as thoroughly, and are necessary for long-term viability.

6 Conclusion

The literature robustly supports the technical feasibility and potential of hybrid systems integrating PV, PEM-EL, and FC technologies for civil engineering applications. Although the energy performance outcomes and environmental benefits are noteworthy, the integration methods for scalable and cost-effective implementation, grounded in validated control methods, are pivotal for the broader adoption of these technologies. As researchers, we identify the synergy between photovoltaic and hydrogen systems as a promising avenue for future decentralized and low-emission energy systems. Critical areas for further investigation include stringent hardware-in-the-loop validation, domain co-simulation, and multisector deployment studies, which are essential for both the commercial realization of energy potential and the technological viability of these systems. Particular attention should be directed towards robust energy management systems, aging studies, and the reintegration of thermal energy. These areas, while undoubtedly relevant, remain underexplored and are likely crucial for ensuring the sustained practicality of operations. Innovations in power electronics, energy management algorithms, and cost-competitive hydrogen production methods are steadily closing the gap between concept and implementation. To support this transition, future research should concentrate on the following four key areas; development of advanced adaptive control strategies, material and design improvements to enhance PEM component lifespan, comprehensive techno-economic and lifecycle assessments and integration models tailored to specific civil engineering contexts.

This research is supported by the German International Cooperation: “La Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH” as part of its project “RELANCE VERTE 2025", and by the National Center for Scientific and Technical Research (CNRST) through the “PhD-ASsociate Scholarship – PASS” program.

References

1. 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. **12**, 4832 (2020). https://doi.org/10.3390/su12124832
2. Y. Venkata Pavan Kumar, S. Naga Venkata Bramareswara Rao, and D. J. Pradeep, Fuzzy-Based Current-Controlled Voltage Source Inverter for Improved Power Quality in Photovoltaic and Fuel Cell Integrated Sustainable Hybrid Microgrids. Sustainability. **17**, 4520 (2025). https://doi.org/10.3390/su17104520
3. H. Bahri, A. Harrag, and H. Rezk, Optimal Configuration and Techno-Economic Analysis of Hybrid Photovoltaic/PEM Fuel Cell Power System. J. New Mater. Electrochem. Syst. **25**, 116–125 (2022). https://doi.org/10.14447/jnmes.v25i2.a05
4. A. Arsalis, G. E. Georghiou, and P. Papanastasiou, Recent Research Progress in Hybrid Photovoltaic–Regenerative Hydrogen Fuel Cell Microgrid Systems. Energies. **15**, 3512 (2022). https://doi.org/10.3390/en15103512
5. C. Ogbonnaya, C. Abeykoon, A. Nasser, A. Turan, and C. S. Ume, Prospects of Integrated Photovoltaic-Fuel Cell Systems in a Hydrogen Economy: A Comprehensive Review. Energies. **14**, 6827 (2021). https://doi.org/10.3390/en14206827
6. S. Vasantharaj, V. Indragandhi, V. Subramaniyaswamy, Y. Teekaraman, R. Kuppusamy, and S. Nikolovski, Efficient Control of DC Microgrid with Hybrid PV—

Fuel Cell and Energy Storage Systems. Energies. **14**, 3234 (2021). https://doi.org/10.3390/en14113234

7. Md. S. Hossain, A. G. Alharbi, K. Z. Islam, and Md. R. Islam, Techno-Economic Analysis of the Hybrid Solar PV/H/Fuel Cell Based Supply Scheme for Green Mobile Communication. Sustainability. **13**, 12508 (2021). https://doi.org/10.3390/su132212508
8. D. S. Vijayan, E. Koda, A. Sivasuriyan, J. Winkler, P. Devarajan, R. S. Kumar, A. Jakimiuk, P. Osinski, A. Podlasek, and M. D. Vaverková, Advancements in Solar Panel Technology in Civil Engineering for Revolutionizing Renewable Energy Solutions—A Review. Energies. **16**, 6579 (2023). https://doi.org/10.3390/en16186579
9. X. Cao, J. Wang, P. Zhao, H. Xia, Y. Li, L. Sun, and W. He, Hydrogen Production System Using Alkaline Water Electrolysis Adapting to Fast Fluctuating Photovoltaic Power. Energies. **16**, 3308 (2023). https://doi.org/10.3390/en16083308
10. M. Koundi, H. El Fadil, Z. El Idrissi, A. Lassioui, A. Intidam, T. Bouanou, S. Nady, and A. Rachid, Investigation of Hydrogen Production System-Based PEM EL: PEM EL Modeling, DC/DC Power Converter, and Controller Design Approaches. Clean Technol. **5**, 531–568 (2023). https://doi.org/10.3390/cleantechnol5020028
11. M. Benghanem, A. Mellit, H. Almohamadi, S. Haddad, N. Chettibi, A. M. Alanazi, D. Dasalla, and A. Alzahrani, Hydrogen Production Methods Based on Solar and Wind Energy: A Review. Energies. **16**, 757 (2023). https://doi.org/10.3390/en16020757
12. G.-I. Giurgi, L. A. Szolga, and D.-V. Giurgi, Benefits of Fuzzy Logic on MPPT and PI Controllers in the Chain of Photovoltaic Control Systems. Appl. Sci. **12**, 2318 (2022). https://doi.org/10.3390/app12052318
13. H. Rezk, N. Kanagaraj, and M. Al-Dhaifallah, Design and Sensitivity Analysis of Hybrid Photovoltaic-Fuel-Cell-Battery System to Supply a Small Community at Saudi NEOM City. Sustainability. **12**, 3341 (2020). https://doi.org/10.3390/su12083341
14. R. M. Ghoniem, A. Alahmer, H. Rezk, and S. As'ad, Optimal Design and Sizing of Hybrid Photovoltaic/Fuel Cell Electrical Power System. Sustainability. **15**, 12026 (2023). https://doi.org/10.3390/su151512026
15. Y. Wang, X. He, Q. Liu, and S. Razmjooy, Economic and technical analysis of an HRES (Hybrid Renewable Energy System) comprising wind, PV, and fuel cells using an improved subtraction-average-based optimizer. Heliyon. **10**, e32712 (2024). https://doi.org/10.1016/j.heliyon.2024.e32712