The Energy Storage Capability of Building Rainscreen Cladding Panels Integrated with Photovoltaic and Reversible Proton Exchange Membrane Fuel Cells

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ABSTRACT: This study forms an integral part of an ongoing doctoral project aimed at developing and assessing building skin solutions intended for use as distributed energy sources. Photovoltaics (PV) have become extensively employed and integrated into buildings to harvest solar radiation and produce electricity. However, a notable challenge with photovoltaics lies in their intermittent nature, which leads to an unreliable and unstable energy supply. As more photovoltaics are introduced to the grid, the "duck effect" emerges, exacerbating the difference between maximum and minimum energy supply in a day, posing a threat to power infrastructure stability. Addressing these issues, one strategy involves the use of batteries, although they are constrained by scalability and degradation concerns. A promising alternative for energy storage in buildings is the Reversible Proton Exchange Membrane Fuel Cell (RPEMFC), which, despite being used in power facilities, has not seen widespread adoption in buildings. Our objective is to design building components that can seamlessly integrate a reversible fuel cell with photovoltaics, creating a self-sufficient system capable of providing renewable energy for the building. This paper presents three significant contributions: (a) The proposal of a building cladding panel with the capability to harvest solar energy, convert it into hydrogen for storage, and subsequently utilize the stored hydrogen to generate electricity. (b) Conceptualization of the building system and an illustration of its functionality within a building context. (c) Execution of simulations using Matlab/Simulink to assess the capability of hydrogen production and storage. The simulations were conducted in two distinct locations, namely Phoenix, Arizona, and Chicago, Illinois. The study suggests that optimal outcomes are not achieved in the hottest weather conditions; specifically, the highest hydrogen production occurred in winter due to larger zenith angles hitting vertical building facades and lower temperatures being conducive to PV-RPEMFC performance.

KEYWORDS: Solar energy, Renewable energy storage, Reversible fuel cells, Building integration

INTRODUCTION

Buildings contribute significantly to global fossil-fuel energy consumption and carbon emissions. Embracing renewable energy sources for power generation presents a compelling prospect for achieving net-zero and carbon-zero buildings. Among the various renewable options for sustainable construction, photovoltaic systems have emerged as a leading technology. One significant obstacle for PV systems is the intermittent and unpredictable nature of solar radiation (Yin et al. 2020). To address the intermittent nature of PV energy, the integration of a reliable energy storage system offers a practical and efficient solution (Suberu et al. 2014, 499-514). While numerous examples and practical projects involve PV systems and electrochemical storage solutions like batteries in architectural projects, our study places a special emphasis on a more scalable, versatile, and environmentally friendly technology to be used in building skins: reversible proton exchange membrane fuel cells (RPEMFC), which store energy in the form of hydrogen (Zhang et al. 2023, 2203). In our study, we investigate the integration of PV and RPEMFC systems into building cladding panels and provide a space-efficient solution that could be installed on existing building skins; therefore, utilizing vast areas of urban building surfaces for harnessing and storing energy.

Electrochemical applications permeate various sectors, including industry, transportation, and building infrastructure, serving as pivotal components for both energy storage and production. Three primary genres of electrochemical devices—batteries, supercapacitors, and fuel cells/electrolyzers—constitute the diverse landscape of this technology. Predominantly, batteries stand out as the most prevalent electrochemical applications, with secondary batteries serving as the primary choice for energy storage due to their charging/discharging ability, operational simplicity, and low maintenance requirements. However, challenges such as limited scalability, degradation, and self-discharging are inherent in their design (Kolosnitsyn and Elena 2008, 506-9). The lithium-ion battery emerges as a promising development, boasting high energy density and an extended life cycle (Xu et al. 2018, 1131-40). Flow batteries, while not commonplace in daily life, find utility as grid energy storage devices owing to their impressive scalability (Weber et al. 2011, 1137-64). Another form of electrochemical application is the supercapacitor, with specific building applications having been developed (Andrés et al. 2022, Berestok et al. 2021). An intriguing example is the photocapacitor, a singular device designed to harvest solar energy and store it within itself. The reported energy density of 1.6 x 10-4 Wh cm-2 and 4.27 Wh cm-2, while relatively low compared to PV-battery systems, underscores its potential. Notably, Vaghasiya et al.'s group (2021) employed 3D-printing technology to transform bricks into a supercapacitor, showcasing an innovative building component that can efficiently store energy.

Fuel cells/electrolyzers, as a distinct group of electrochemical applications, exhibit notable scalability and harness the clean energy storage capabilities of hydrogen. This makes them a viable option for producing and storing energy in a pristine form. Studies on building cogeneration systems, such as those by Ashari et al. (2012), Chahartaghi and Kharkeshi. (2018, 805-17), and Chadly et al. (2021), underscore the versatility and applicability of fuel cells/electrolyzers. Additionally, innovative approaches, such as You et al.'s (2019) development of bricks utilizing urine for electricity production through microbial fuel cells, further showcase the evolving landscape of electrochemical applications.

After an extensive examination of various electrochemical applications, our inclination for advancing building technology centers on the reversible proton exchange membrane fuel cell (RPEMFC). This innovative technology seamlessly integrates the functions of an electrolyzer and a fuel cell, enabling it not only to split water into hydrogen and oxygen but also to convert hydrogen back into electricity. In the prototype developed in this study, instead of utilizing a market available RPEMFC, two cells—a electrolyzer and a fuel cell—were employed to represent the electrochemical conversion process. This choice is justified by the remarkable scalability of the RPEMFC and its ability to store energy in the super-clean form of hydrogen, emitting no CO2 upon combustion. In contrast to other fuel cell types with stringent operational requirements, such as the Solid Oxide Fuel Cell (SOFC) that demands temperatures ranging from 600 to 1000°C, the RPEMFC operates at relatively low temperatures. This characteristic makes it well-suited for ambient conditions commonly encountered in buildings.

1.0 STUDY OBJECTIVES

The primary objective of this investigation is to propose and assess building skin solutions engineered to adeptly capture, transform, and store renewable clean energy through the integration of photovoltaic (PV) technology and reversible proton exchange membrane fuel cells (RPEMFC). Specifically, this study aims to:

(a) Conceptualize and develop prototypes or propose potential designs of building skins cladding with PV-RPEMFC integration. These claddings would be capable of harvesting, converting, and storing solar energy while addressing architectural and safety considerations.
(b) Establish a system that seamlessly integrates these innovative panels into the energy supply and storage infrastructure of entire buildings.
(c) Utilize Matlab/Simulink to simulate the energy efficiency of a building facade incorporating a PV-RPEMFC system. Evaluate the system's hydrogen production capabilities in two distinct climate scenarios and conduct a comparative analysis.

2.0 PV-RPEMFC CLADDING PANEL PROTOTYPE DESIGN AND BUILDING SYSTEM DESCRIPTION

2.1. Preliminary demonstrator

A preliminary prototype has been constructed to elucidate the operational principles of the system. Further details can be found in the initial investigation by Zhang and Azari (2025). The reversible fuel cell utilized in this prototype is capable of functioning as both an electrolyzer and a fuel cell simultaneously. The hydrogen production was measured at approximately 15.7 W/m2, resulting in an energy conversion efficiency of 8.76%. Due to the demonstrator's primary purpose of illustrating system functionality, potential issues such as gas leakage and connection problems may have led to imprecise measurements, rendering the results inconclusive for validating simulation outcomes. A new prototype is currently under development, with our proposed design for a PV-RPEMFC panel outlined in the subsequent section.

Figure 1: A demonstrator of using RPEMFC to store energy. Author: (Zhang and Azari 2025)

2.2 The PV-RPEMFC cladding panel prototype design

The proposed modules are designed to be installed on building surfaces, particularly on facades in urban areas where solar energy can be harvested. The modules can be installed on existing buildings or newly constructed facades. The PV-RPEMFC based cladding units are composed of multiple layers, starting from the outermost layer, which is made up of photovoltaic cells, and followed by RPEM fuel cells (Figure 2). The photovoltaic cells are responsible for harvesting solar radiation and converting it into electricity. This electricity can either be used immediately or converted into chemical energy through PEMFC.

The cladding prototype employs SUNAPEX monocrystalline silicon as the PV panel, with each panel measuring 38 cm in length and 34 cm in width (“Amazon.Com: Sunapex 20W Solar Car Battery Trickle Charger & Maintainer” n.d.). The PV panel operates at 18 V with a maximum power output of 20 W.

For the reversible fuel cell working process representation, an electrolyzer and fuel cell are used. The PV panel is matched with a PEM electrolyzer to convert electricity into hydrogen for energy storage. The chosen electrolyzer from Fuelcellstore (“PEM Water Electrolyzer 1-Cell Stack - Assembled,” n.d.) is a PEM water electrolyzer with a 1-cell stack and an input power range of 10-80 W, suitable for the PV output power. The active area of the PEM water electrolyzer is 25 cm2, generating hydrogen at a rate ranging from 0 to 370 mL/min.

To connect the PEMFC to the photovoltaics, wires are employed, with the anode and cathode connected to the positive and negative sides of the PV cells, respectively. During the initial energy conversion of RPEM fuel cells, hydrogen and oxygen are produced. A solid-H BL-18 metal hydride storage system (“BL-18 Metal Hydride,” n.d.) is utilized for hydrogen storage due to its small volume and significant storage capacity. This metal hydride storage cylinder, around 8 inches in length (slightly longer than a pen), has a storage capacity of 18 liters of hydrogen. The product is known for its safety in storing flammable hydrogen gas. The cylinder's size allows for a slight increase to release hydrogen without the need for a large container and compressor in the traditional hydrogen storage method.

During nighttime when solar energy is unavailable, PEM fuel cells use the stored hydrogen and air to generate electricity. The PEM fuel cell chosen for demonstration is the PEM Flex-Stak Assembled from Fuelcellstore (“Flex-Stak Assembled,” n.d.), featuring a 1-cell stack with an active area of 10 cm2 and a nominal output power ranging from 0.25 to 0.35 W.

The cladding units serve as energy generators, producing electricity through a combination of solar energy harvesting and PEM fuel cell technology. This approach offers a promising solution for sustainable building design and energy generation.

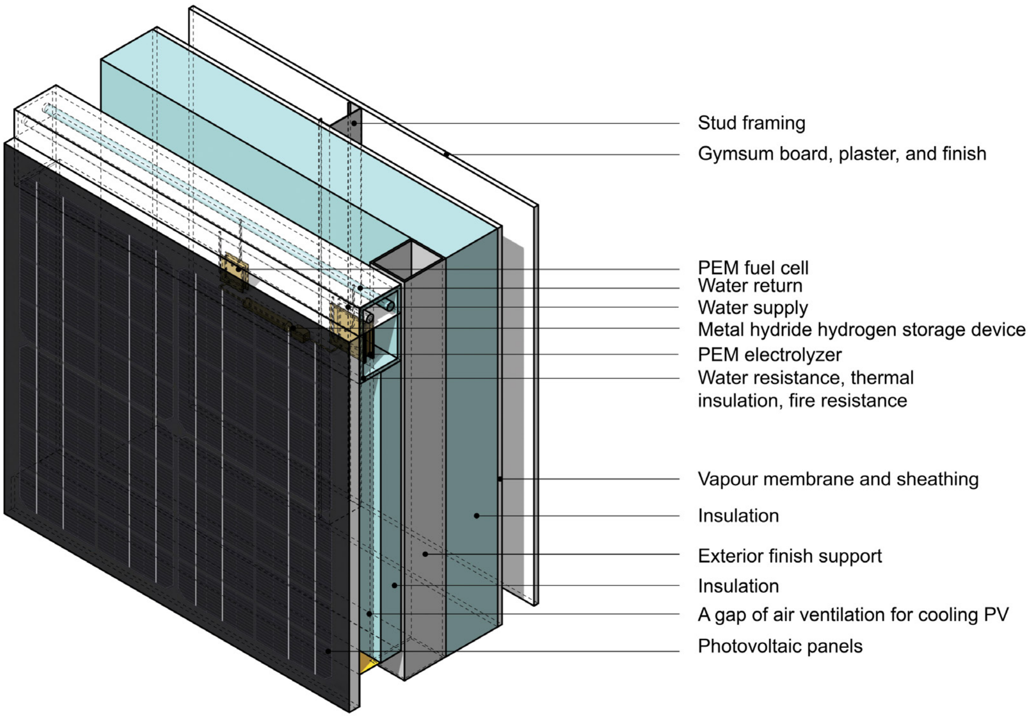


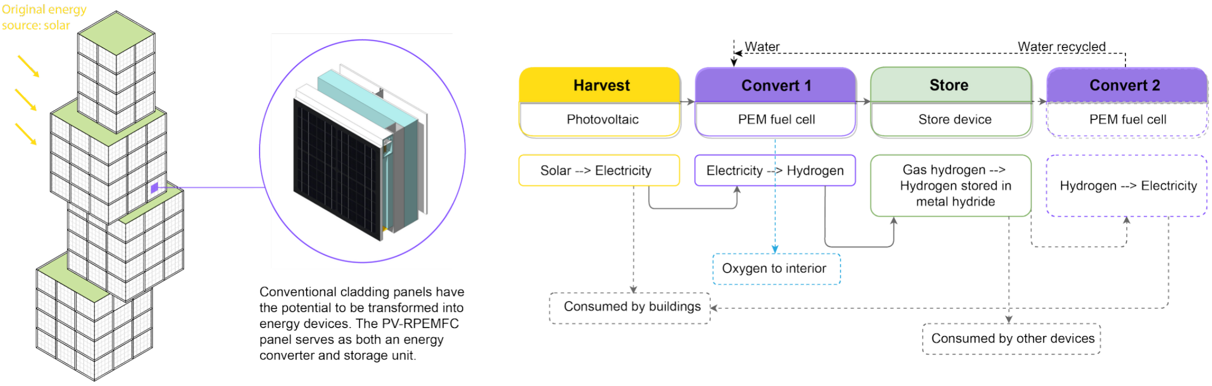
Figure 2: Proposed PV-RPEMFC. The figure shows the conceptual layering of PV-RPEMFC cladding panels, while the functionality is described in the text. Source: (Author 2024)

2.3. Building system description

Cladding panels stand out as a promising application for building skins seamlessly integrated with PV-RPEMFC technology, particularly in urban where large area of surfaces can serve as solar energy receptors. Rain-screen cladding, typically employed as a protective outer layer for buildings, gains significant value when equipped to harvest solar energy, especially amid today's energy scarcity challenges.

When configuring PV-RPEMFC as cladding panels, adherence to specific codes such as the International Building Code and International Solar Energy Provision becomes imperative. Factors such as weather resistance, water resistance, and fire protection assume critical importance for these components. Safeguarding auxiliary wires and water circulations is essential for safety, addressing concerns such as frost protection in winter and preventing overheating in summer. To address these considerations, we propose a protective channel installed along each row of PV-RPEMFC panels. This channel is designed to be electrically insulated and fire-resistant, eliminating the need for additional hydrogen tanks or compressors, as the hydrogen is already stored within the cladding panels themselves.

In essence, PV-RPEMFC panels serve a dual purpose—they function not only as cladding panels but also as devices for harvesting and storing energy. The generated electricity is subsequently harnessed and conveyed to the buildings for consumption. Installation-wise, these panels are affixed or installed in a manner similar to conventional cladding panels.



Conventional cladding panels have the potential to be transformed into energy devices. The PV-RPEMFC panel serves as both an energy converter and storage unit.

Figure 3: The energy conversions in the PV-RPEMFC system. Source: (Author 2024)

3.0 SIMULATION

3.1. Simulation setup

The simulation utilized the U.S. Department of Energy’s prototype residential building model – multi-section electric furnace family (Department of Energy, n.d.). EnerglyPlus weather data EPW locations for Phoenix and Chicago were employed to conduct an EnergyPlus building energy consumption simulation. The energy consumption per conditioned building area was found to be 13.14 kWh/m2 in Phoenix and 18.81 kWh/m2 in Chicago, with a conditioned building area of 1568.72 m2 and a south façade total area of 448.24 m2, including an opaque wall area (non-glazing area for installing PV-RPEMFC panels) of 401.18 m2. It was assumed that 100 square meters of the opaque wall on the south façade would be covered with PV-RPEMFC panels. Subsequently, an energy simulation using Matlab/Simulink was conducted to assess the potential energy contribution from these panels to buildings.

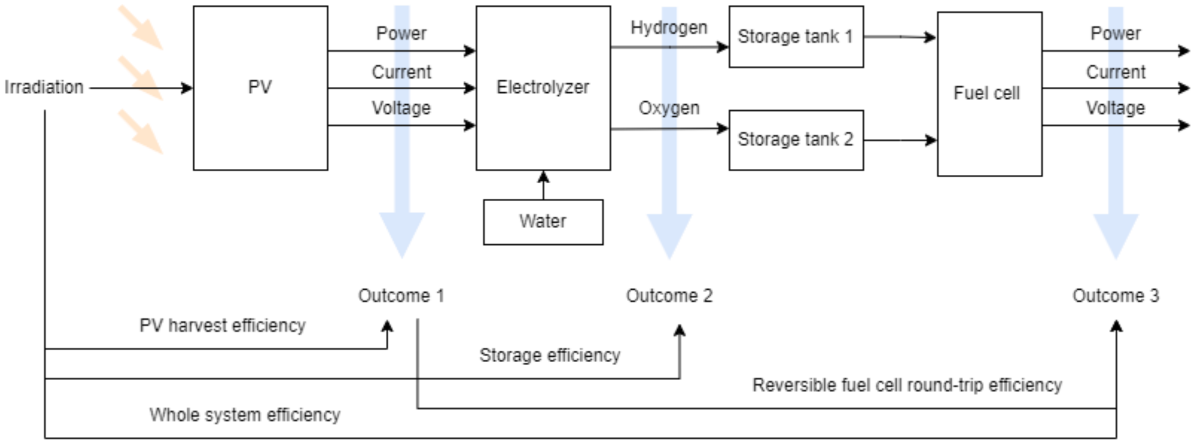


Figure 4: Matlab/Simulink Simulation framework. Source: (Author 2024)

A MATLAB/Simulink diagrammatic model was employed to estimate the energy storage capacity of the system. Leveraging MATLAB's robust mathematical capabilities and Simulink's user-friendly interface for researchers, the primary objective was to gain insights into the performance of energy harvesting, storage, and conversion within this multi-family residential building context.

The simulation encompassed two distinct climate zones: Chicago, categorized as climate zone 5A (cool humid) (ASHRAE 2020), and Phoenix, classified as climate zone 1B (very hot dry) (ASHRAE 2020). Key inputs for the model included daily irradiation, temperature, wind speed, from EnergyPlus, specifically 'Surface Outside Face Incident Solar Radiation Rate per Area [W/m2] (Hourly)', 'Site Outdoor Air Drybulb Temperature [C] (Hourly)', and ‘Site Wind Speed [m/s] (Hourly)’. The energy source, radiation, was directed to the PV module to generate electricity, which was then used to split water and produce hydrogen stored in a tank. The fuel cell later utilized this stored hydrogen to generate electricity once again.

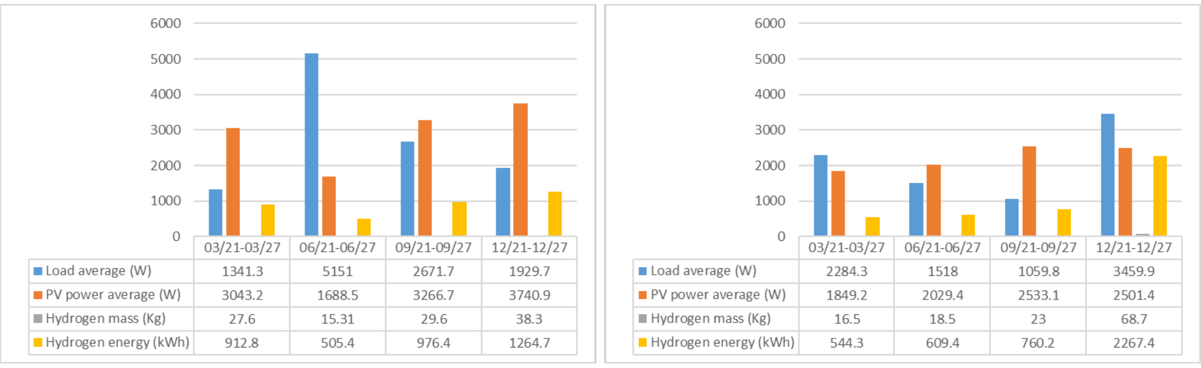
In the Matlab/Simulink model, major components (Figure 4), include the PV panels, PEM electrolyzer, and PEM fuel cell. The PV model incorporated ambient conditions (Ayaz et al. 2014, 1-6), while the PEM electrolyzer Simulink model was based on Albarghot et al.'s system model (2016). The PEM fuel cell Simulink model drew from Mathworks' system model (Mathworks 2023). To streamline the simulation process, it was assumed that all solar power generated by the PV system was exclusively dedicated to hydrogen production rather than directly supplying electricity to the building. Subsequently, all produced hydrogen was consumed for electricity generation. The simulation focused on the south façade of the building in order to assess potential impacts under different climatic conditions. Simulation duration spanned a week in each season: March 21st to March 27th, June 21st to June 27th, September 21st to September 27th and December 21st to December 27th. Expected outcomes included hydrogen production from the PV-electrolyzer process and electricity generation from the hydrogen-fuel cell process.

3.2. Results and Discussion

The simulated results suggest that summer is not the optimal time for harvesting hydrogen and that winter obtains the highest amount of hydrogen in both Phoenix and Chicago. This can be attributed to two main factors. Firstly, the installation of PV for solar energy harvesting on vertical façades leads to a larger zenith solar during winter, resulting in more irradiance hitting the vertical surfaces. Additionally, the temperature coefficient of power plays a significant role in influencing photovoltaic efficiency, with lower temperatures in winter leading to higher efficiency. Analysis of table 1 and figure 5 indicates that in Phoenix, summer requires more cooling load due to hot weather but the PV-RPEMFC system may not generate enough energy for residential building operation. In this scenario, all the electrical energy generated by the photovoltaic system will be directly utilized by the building. In Chicago, winter needs more heating load and does not result in hydrogen storage. However, when photovoltaics produce more power than building load under other circumstances, hydrogen can be produced for further use.

This research primarily aims to understand how climate variables, particularly solar radiation and temperature fluctuations, impact the hydrogen production output. It is crucial to acknowledge certain limitations inherent in the simulation results. The simulations were carried out using default settings in Matlab/Simulink for energy estimation, which may not precisely depict the performance of a specific commercial reversible fuel cell in real-world conditions. For enhanced accuracy, future simulations should model each component in the system based on manufacturer specifications. Our subsequent step involves constructing a Matlab/Simulink model that is more precise and aligns closely with the characteristics of the products described in the text. The metal hydride storage is tailored for a specific storage function, differing from the traditional approach of compressed hydrogen storage. However, even with meticulous modeling, disparities may persist due to factors such as internal resistance or other energy losses.

Table 1: A comparison between two locations: Phoenix (left) and Chicago (right). Source: (Author 2024)



	03/21-03/27	06/21-06/27	09/21-09/27	12/21-12/27
Load average (W)	1341.3	5151	2671.7	1929.7
PV power average (W)	3043.2	1688.5	3266.7	3740.9
Hydrogen mass (Kg)	27.6	15.31	29.6	38.3
Hydrogen energy (kWh)	912.8	505.4	976.4	1264.7

	03/21-03/27	06/21-06/27	09/21-09/27	12/21-12/27
Load average (W)	2284.3	1518	1059.8	3459.9
PV power average (W)	1849.2	2029.4	2533.1	2501.4
Hydrogen mass (Kg)	16.5	18.5	23	68.7
Hydrogen energy (kWh)	544.3	609.4	760.2	2267.4

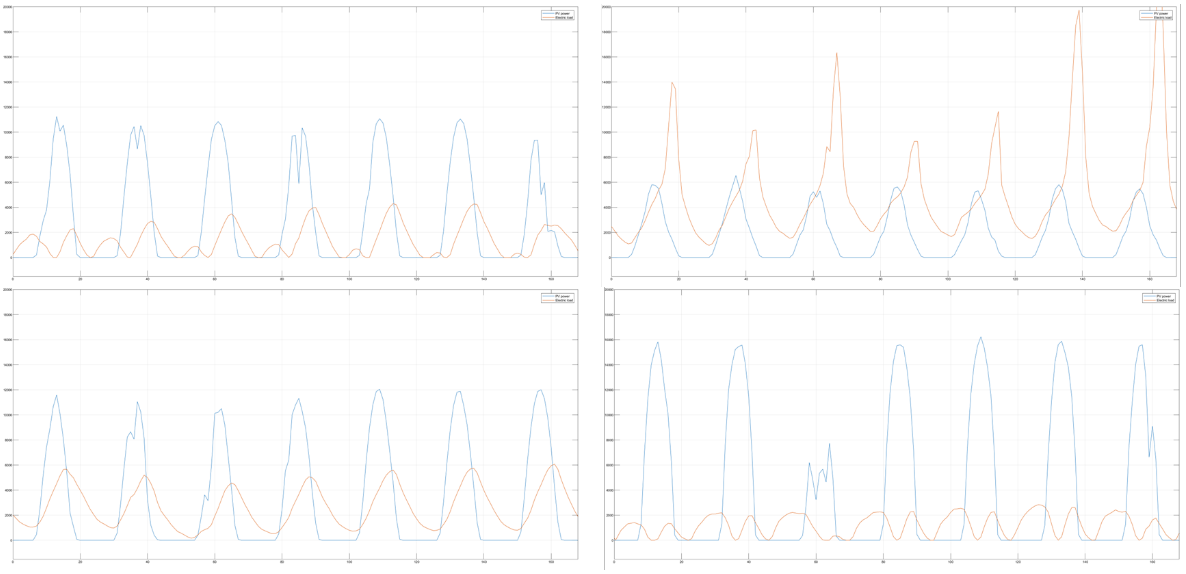


Figure 5: Phoenix: PV power (blue) and building load (orange). Top left: March, top right: June, bottom left: September, bottom right: December. Source: (Author 2024)

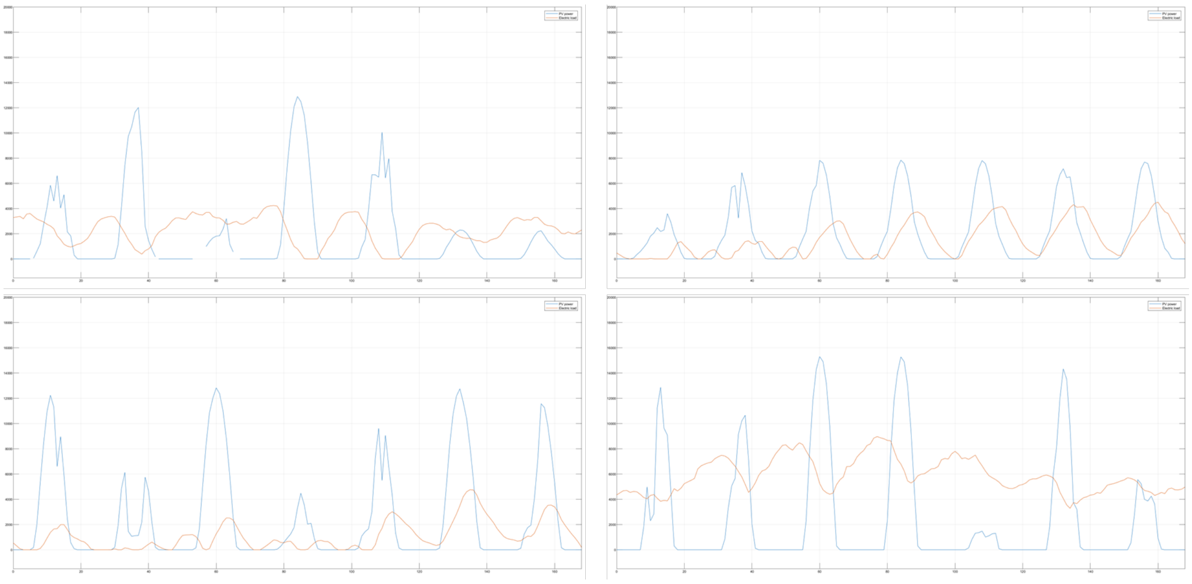


Figure 6: Chicago: PV power (blue) and building load (orange). Top left: March, top right: June, bottom left: September, bottom right: December. Source: (Author 2024)

CONCLUSION

To date, the research introduces a potential design for PV-RPEMFC cladding panels capable of harvesting solar energy, converting it into clean energy in form of hydrogen, and storing hydrogen. The stored hydrogen is then utilized to generate electricity, completing an energy storage process within buildings. In contrast to the conventional method of storing solar energy in batteries, RPEMFC offers scalability and does not involve the emission of greenhouse gases. However, given the current cost of reversible fuel cells, further electrochemical research is needed to develop more cost-effective and highly energy-efficient cells for widespread use in construction.

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