

INTEGRATED PHOTOVOLTAIC WITH REVERSIBLE PROTON EXCHANGE MEMBRANE FUEL CELL-BASED BUILDING CLADDING SYSTEMS FOR HYDROGEN AND OXYGEN PRODUCTION

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ABSTRACT: The latest data from the US Energy Information Administration (EIA 2022) shows that energy consumption from buildings accounted for 37 percent of total energy consumption, of which 79 percent is derived from fossil fuels that cause 73 percent of greenhouse gas emissions. According to the US government (US Department of State and US Executive Office of the President 2021), there is a need to investigate renewable energy and carbon neutralization. This paper reports on an ongoing doctoral project in architecture that examines the application of reversible fuel cells in buildings and proposes a system for integrating photovoltaics with reversible fuel cells into building envelopes. This system has been designed to produce clean energy in the form of electricity and hydrogen, as well as oxygen for buildings to improve indoor air quality. Hydrogen is regarded as a possible energy storage medium for transitioning the world to a zero-carbon environment. Among six common fuel cells, proton exchange membrane fuel cells (PEMFCs) are straightforward to use and lead to a relatively higher energy conversion rate of 40–60% (EERE n.d.). Researchers have previously studied some electrochemical applications for building energy generation and storage. In this research, we aimed to explore the potential of reversible proton exchange membrane fuel cells for building skin applications by constructing a physical prototype and measuring its efficiency. To confirm the potential of reversible fuel cells for building skin applications, our team constructed an initial prototype of a reversible PEMFC-based cladding system. The prototype was 15.24 cm × 15.24 cm (6 in. × 6 in.) and contained four photovoltaic cells on the exterior side and four reversible PEMFCs on the interior side. The independent variable was radiation, and the dependent variables included oxygen volume, hydrogen volume, and energy conversion efficiency. The irradiance on the day of the experiment was measured at 156.6 W/m² (49.6 Btu/(hr.ft²)). The hydrogen energy output of the system was determined to be 15.7 W/m² (5.0 Btu/(hr.ft²)), yielding an energy conversion rate of 8.76 percent. The energy conversion rate of a traditional PV system with batteries is 15–20 percent. While the proposed system cannot currently compete with commercial PV-battery systems, energy conversion efficiency may be improved through future research. In addition, the scalability of reversible fuel cell storage is better than traditional batteries, as a byproduct of the proposed system, oxygen can be introduced into HVAC systems in buildings to improve indoor air quality. We envision a future in which diverse and clean energy generation and storage technologies have been adopted in building skins to help supplement or replace traditional sources of energy.

KEYWORDS: hydrogen production, building claddings, reversible proton exchange membrane fuel cell.

INTRODUCTION

Residential and commercial buildings account for 37 percent of all US primary energy use, highlighting the need for energy-efficient solutions in the built environment (EIA 2022). While energy-saving measures are important, it is also necessary to reduce the consumption burden, especially in areas with high energy demand. Recently, onsite energy generation through distributed energy resource (DER) technologies has gained popularity as a complementary energy source to supplement energy demand.

The centralized and inflexible nature of the grid system poses challenges, especially in geographically inconvenient areas. However, it is not solely rural locales that can benefit from DER. Urban areas can also leverage onsite energy generation and storage to serve as backup or supplement, thereby alleviating pressure on the grid. Yet, despite the integration of renewable energy into the built environment, the intermittent nature of renewable sources may not always align with the energy-use profile of buildings. One potential solution is the use of electricity storage, commonly achieved through batteries. However, due to concerns such as battery degradation and limited scalability, reversible fuel cells have emerged as an alternative electricity storage option, devoid of the issues associated with batteries. The reversible PEM fuel cell discussed in this paper utilizes hydrogen as a form of storage, offering the advantage of zero CO₂ emissions upon consumption.

In addressing the limitations of battery storage in buildings, this study endeavors to investigate a proposed cladding prototype that integrates photovoltaic (PV) technology and a reversible PEM fuel cell. The envisioned integrated system is specifically crafted to capture solar energy, transform it into hydrogen for storage, and subsequently convert the stored hydrogen back into electricity for building applications. A small-scale prototype was developed to visually demonstrate the intricacies of the energy conversion process and to quantify the storage capacity.

Upon comparing the cladding panel design with conventional building energy storage systems, it becomes apparent that this cladding panel offers versatility. Not only can it be seamlessly integrated into new building envelopes, but it also presents a viable solution for building retrofit scenarios where space constraints limit the installation of traditional storage systems. This adaptability provides a flexible and efficient solution for buildings with restricted space.

1. ELECTROCHEMICAL APPLICATIONS IN STATE OF THE ART BUILDINGS

Chemical-to-electricity conversion is crucial for transforming chemical sources into usable electricity or converting electricity to chemical forms. This process involves burning fuel or chemically reacting fuel with other substances to generate electricity. Batteries store energy in chemical solutions and convert it into electricity through a chemical reaction process when electricity is needed. In buildings, batteries are commonly used to store energy in photovoltaic (PV) systems. Secondary batteries are also commonly used for PV energy storage in buildings. Lithium-ion and lead-acid batteries are two commonly used storage options for residential buildings, as they are relatively stable, have long life cycles, and are economical and safe. However, the degradation of lead or acid in batteries over time leads to decreased storage capacity. In contrast, reversible fuel cells do not suffer from this issue because their storage systems are independent of their generating devices (Smith 2000). Nowadays, PVs are installed with battery systems for storage. The system energy conversion efficiency is defined as the energy conversion rate of PVs multiplied by the efficiency of the battery. The PV efficiency average is 20 percent, and battery efficiency is around 85 percent. That means that the solar battery system's total energy conversion efficiency is 17 percent.

Regenerative fuel cells, or reversible fuel cells, are devices that have both electrochemical and galvanic properties, making them rechargeable and able to be charged and discharged many times. Compared to traditional rechargeable batteries

of the same weight, reversible fuel cells have a higher energy capacity (Miltitsky et al. 1999). A recent study by Chadly et al. (2022) evaluated the cost-effectiveness of lithium-ion batteries (LIB), proton exchange membrane fuel cells (PEMFC), and solid oxide fuel cells (SOFC) using the levelized cost of energy storage (LCOS) metric. The LCOS results, without considering degradation, indicated that it cost 41.79 ¢/kWh for PEMFC, 28.29 ¢/kWh for SOFC, and 27.35 ¢/kWh for LIB. SOFC is comparable to batteries in terms of LCOS. For the long term, considering degradation, scale-up potential, and a low tolerance for the environment of batteries, PEMFC might improve reliability and resiliency for stand-alone buildings.

Fuel cells are categorized into six types based on their electrolytes: polymer electrolyte membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), and microbial fuel cell (MFC). Each works in different conditions but has similar energy efficiencies, ranging from 40 to 60 percent. According to their different operational requirements, these fuel cells are designed for different applications. Among the types of fuel cells, PEM fuel cells can be operated in an ambient environment without any additional heat increase for starting up the system. Azadi and Azari (2020) has proposed a design of an artificial leaf-based cladding system for buildings. The outer layer is photovoltaic, producing electricity, which triggers electrochemical reactions in other layers, combining H₂O and CO₂ to produce natural gas and oxygen. Overall, these studies showcase the potential of reversible fuel cells in buildings for electricity generation and storage, with PEM fuel cells being popular choices due to their high efficiency and versatility. However, further research and improvements are necessary to create effective and sustainable reversible fuel cell cogeneration systems for buildings.

2. METHODOLOGY

The aim of this research is to explore the feasibility of integrating reversible proton exchange membrane (PEM) fuel cells with building cladding systems as a sustainable energy solution. The first step involved designing a building system that incorporated the reversible fuel cells and demonstrated how they would function within a building. A prototype was then developed and tested to ensure that the cladding unit could operate effectively in real-world conditions. The energy conversion rate of the system was estimated through theoretical calculations and experimental measurements. By integrating reversible PEM fuel cells with building cladding systems, it may be possible to increase the use of renewable energy sources and reduce reliance on the electrical grid. Furthermore, such a system may have the potential to be more cost-effective and environmentally friendly than traditional PV and battery systems.

2.1. SYSTEM 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 PEMFC-based cladding units are composed of multiple layers, starting with an outermost layer made up of photovoltaic cells and followed by reversible PEM fuel cells. The photovoltaic cells are responsible for harvesting solar energy and converting it into electricity. This electricity can either be used immediately or converted into chemical energy through reversible PEM fuel cells.

To connect the PEM fuel cells to the photovoltaics, wires are used, with the anode and cathode connected to the positive and negative sides of the PV cells, respectively. Hydrogen and oxygen are produced during the initial energy conversion process of PEM fuel cells. Within the building, a hydrogen storage system can either compress or liquify the hydrogen for future use. During the nighttime, when no solar energy is available, PEM fuel cells can use the stored hydrogen and air to produce electricity again.

The cladding units are energy generators, producing electricity through solar energy

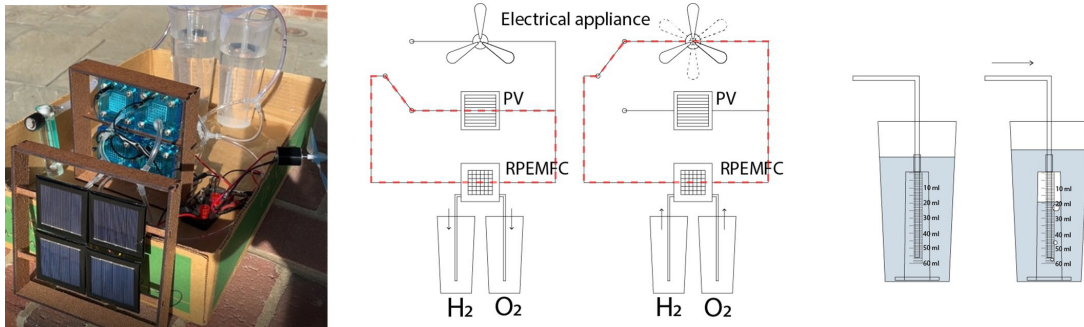


Figure 1: From left to right: A) initial reversible PEMFC-based energy production and storage prototype; B) current diagrams (left: water is split into hydrogen and oxygen in electrolysis mode; right: hydrogen and oxygen react to produce electricity in galvanic mode); and C) gas storage devices, where gases push down water in the syringe to be stored in the closed space. Source: Author 2024.

harvesting and PEM fuel cell technology. This innovative approach offers a promising sustainable building design and energy generation solution.

2.2. PROTOTYPE

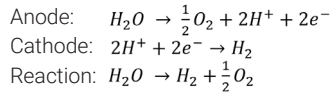
The first prototype was 15.24 cm × 15.24 cm (6 in. × 6 in.) frame size and consisted of four 5.4 cm × 5.4 cm (2.13 in. × 2.13 in.) PV solar cells, four 5.4 cm × 5.4 cm (2.13 in. × 2.13 in.) reversible PEM fuel cells, wires, a knife switch, water, gas tubes, and cups for gas storage. The four PV cells were arranged at the outer layer of the unit and fixed on a 15.24 cm × 15.24 cm (6 in. × 6 in.) wood frame. The next layer of the unit contained the reversible PEM fuel cells. Corresponding wires, water pipes, and gas pipes were all connected in appropriate positions. Storage cups were also connected to the reversible PEM fuel cells. The PV cells were functional when the unit was in electrolysis mode (also called charging mode). The fuel cells split water into hydrogen and oxygen; thus, the unit could work in the daytime when solar energy is available. The PV cells were inactive when the unit was in galvanic mode (also called discharging mode). The reversible PEM fuel cells would consume hydrogen to produce electricity; thus, the unit could work in the evening without sunlight. Figure 1 shows the prototype assembly and the current diagrams for electrolysis and galvanic modes.

2.3 EXPERIMENTAL DESIGN

The objective of the experiment was to verify that the assembled PV and reversible PEM fuel cell cladding system could function in the ambient built environment. Solar irradiance was measured as input values to quantify the original energy sources. Solar radiation input would depend on the weather and the context of the building, such as whether any shadows might influence the input value. We tested the prototype under sunny conditions, meaning there was sufficient solar radiation for the system to realize the energy conversion process. An LI-COR LI-1500 light sensor logger with an LI-200R pyranometer measured irradiance. The other input variable was water. Water would be the chemical reaction source, as it contains hydrogen and oxygen elements that are the raw materials for the subsequent production of hydrogen and oxygen gas. The expected outputs of the experiment were hydrogen gas and oxygen gas, which were stored in the containers shown in Figure 1C.

There were two tubes on each side of the fuel cell for supply. Water was injected into the oxygen side by a syringe. The instructions for PEM fuel cell production specified injecting water into the top tube and filling the cell with the water until water flows out of the bottom tube. We injected 2.2 ml of water into the oxygen side of the PEM fuel cell. Water was distributed on the surface of the PEM membrane. The reaction occurred

automatically due to the catalyst on the membrane, requiring no further action after the water was added. The reactions in the system can be represented as:



The dependent variables for the output were hydrogen gas and oxygen gas. The volumes of hydrogen gas and oxygen gas were measured by a storage device (Figure 2C). To ensure that the volume was comparable, the volume was converted to standard ambient temperature and pressure (SATP) conditions (1 atmosphere of pressure [atm] and 25 °C, or 298.15 K) by the combined gas law. The outputs were then compared with the theoretical results.

3. THEORETICAL EVALUATION AND EXPERIMENTAL RESULTS

3.1. SYSTEM ENERGY CONVERSION THEORETICAL ANALYSIS

The PV cells used for the experiment are made of polycrystalline silicon. The literature shows that the efficiency of this type of PV is between 13 and 16 percent (American Solar Energy Society 2021). For theoretical estimates of the proposed system, 15 percent PV energy conversion efficiency was used.

The hydrogen production rate of the reversible PEM fuel cells is expected to be 7 ml/min, which means this amount of hydrogen can be produced under sufficient conditions with enough power, suitable water supply speed, and ideal ambient conditions such as temperature. PEM electrolyzer efficiency is reported to be around 70 to 80 percent. For theoretical estimates of the proposed system, 75 percent was used. Therefore, energy storage efficiency is the product of PV and electrolyzer efficiency, or 11.25 percent.

3.2. FUEL CELL POTENTIAL

The following are PEMFC theoretical potential calculations, under 1 atm and at 25 °C (77 °F, 298.15 K).

Gibbs energy of reaction:

$$\begin{aligned} \Delta_r G^0 &= \sum v \Delta_f G^0 (\text{products}) - \sum v \Delta_f G^0 (\text{reactants}) \\ &= -237.1 \text{ kJ/mol} \end{aligned}$$

Standard electrode potential:

$$E^0 = - \frac{\Delta_r G^0}{vF} = - (-237100) / (2 \times 96485) = 1.229 \text{ V}$$

3.3. HYDROGEN AND OXYGEN MEASUREMENTS

The experiment was conducted on November 4th, 2022, at 15:00 and a temperature of 20 °C. During the experiment, 17 ml of hydrogen and 7 ml of oxygen were collected within 20 minutes. The amount of heat that can be produced from 17 ml of hydrogen depends on the conditions under which it is burned. Assuming that the hydrogen is burned in the air at SATP, the heat output can be calculated using the higher heating value (HHV) of hydrogen, which is 141.80 MJ/kg (61,000 Btu/lb) (Kayfeci et al. 2019).

To convert 17 ml of hydrogen to kg, the density of hydrogen at SATP, which is 0.0813 kg/m³ (0.051 lbf/ft³), must be known. Therefore, 17 ml of hydrogen is equal to 1.38 x 10⁻⁶ kg. The amount of energy that can be produced by this quantity of hydrogen under HHV is:

$$1.38 \times 10^{-6} \text{ kg} \times 141.80 \text{ MJ/kg} = 199.46 \text{ J}$$

Therefore, burning 17 ml of hydrogen at SATP can produce approximately 199.46 Joules of heat energy.

During the 20-minute experiment, 195.68 J of hydrogen was produced. This translates to an energy production rate of 0.16 W or 160 mW. The preliminary prototype covered a total working area of 5.4 cm x 5.4 cm x 4 = 116.64 cm² = 0.01166 m² (2.13 in. x 2.13 in. x 4 = 18.15 ft²). Thus, the power density of the prototype is:

$$0.16 \text{ W}/0.01166 \text{ m}^2 = 13.72 \text{ W/m}^2 (4.35 \text{ Btu/ft}^2)$$

Therefore, every square meter of the reversible proton exchange membrane fuel cell (RPEMFC) prototype can provide 13.72 W/m² of energy.

3.4. ENERGY CONVERSION EFFICIENCY

The objective of this task is to determine the efficiency of the solar-to-fuel conversion process. The solar irradiance on the PV surface was measured using an irradiance meter. To calculate the solar-to-fuel conversion efficiency, we used the amount of hydrogen gas from the previous task, which can be converted into heat energy; then, we divided the energy produced by burning the hydrogen gas by the measured irradiance. This efficiency ratio will provide us with an estimate of the amount of fuel that can be generated by the energy conversion system.

On the day of the experiment, the measured irradiance was 156.6 W/m². We converted 17 ml of hydrogen gas to heat energy and calculated the energy produced per unit area, which was 13.72 W/m². This means that 13.72 W/m² of chemical energy was generated from 156.6 W/m² of solar radiation. Therefore, the total solar-to-fuel conversion efficiency was calculated to be 8.76 percent.

3.5. DISCUSSION

Based on the calculations and experimental results, there was a discrepancy between the expected energy storage conversion efficiency of 11.25 percent and the experimental result of 8.76 percent. While the experiment confirmed that the assembly of PV and reversible PEM fuel cells could work well in the built environment, the discrepancy raises some possible concerns.

One possible reason for this discrepancy is the insufficient number of PV cells to provide enough power for the reversible fuel cells to produce hydrogen. In the prototype, each reversible PEM fuel cell corresponded to only one PV cell, which did not meet the PEM fuel cell's input voltage requirement of 1.8³ V DC power and current requirement of 0.7 A. The Aoshike photovoltaic cell used in the prototype only provided 2 V of potential and 0.13 mA of current. Another reason for the discrepancy could be the technical barriers faced by the fuel cell, such as chemical crossover, transfer coefficient, mass transfer limitation, and internal resistance. These factors can influence fuel cell performance and affect conversion efficiency. Lastly, the airtightness of the prototype unit was not tested, so it is highly possible that air leakage occurred during the experiment. This could have resulted in a loss of hydrogen and affected the efficiency of the system.

Overall, these factors may have contributed to the observed discrepancy in energy storage conversion efficiency between the expected and experimental results. Further research is needed to optimize the PV and reversible PEM fuel cell assembly and to minimize any technical barriers that may limit the efficiency of the system.

4. NEXT STEPS

In the previous experiment, we obtained the total system energy storage efficiency. However, it is unclear which component(s) of the prototype caused energy loss. Therefore, we plan to measure the efficiency of each part step by step, compare the

specifications of their manufacturers, and adjust the prototype to achieve maximum efficiency conversion.

The PV system efficiency, η_{pv} , is typically measured under stable light and temperature conditions. However, in real-world scenarios, weather conditions can affect efficiency. To test the PV system's performance, we will measure the incident solar irradiance using an LI-COR LI-1500 light sensor logger with an LI-200R pyranometer, as done in the preliminary study. The output voltage and current will be measured using a voltage meter and current meter, respectively. Finally, we will calculate the PV system's energy conversion rate by dividing the product of voltage and current by the incident solar irradiance and multiplying by 100 percent.

The reversible PEMFC's electrolytic mode efficiency (η_{ec}) (charging) is defined as the heat produced by hydrogen divided by the electrical energy supplied. To measure this efficiency, we will use syringes to store hydrogen and oxygen in temporary devices. Syringes will show the volume of hydrogen collected in the experiments, and the mass of hydrogen can then be calculated. According to literature value, one kilogram of hydrogen burned will produce 141.80 MJ heat. Hence, the energy conversion rate can be calculated by:

$$\begin{aligned} \text{Input electricity} &= \text{voltage} * \text{current} \\ \text{Electrolytic mode efficiency } (\eta_{ec}) &= (m * 141.80 \text{ MJ}) / \text{input electricity} \end{aligned}$$

The system energy storage efficiency is the product of η_{pv} and η_{ec} . As no converter is involved in this process, converter efficiency is not included.

The reversible PEMFC and redox flow battery's galvanic mode efficiency (η_{fc}) (discharging) is defined as electricity produced divided by hydrogen consumed. To measure this efficiency, the system will consume all hydrogen obtained from the electrolytic mode. The galvanic mode efficiency is electricity divided by hydrogen energy. Electricity power is defined as output voltage multiplied by output current.

By analyzing each step, we can identify where energy is wasted. From the experimental measurement, we can also use the results for computational simulation in future whole-building energy assessments and system optimization.

5. CONCLUSION

The successful prototype design and experimental testing in this research demonstrate that it is possible to integrate a fuel cell stack with a building cladding system. This breakthrough opens new avenues for commercial product development, with the aim of creating a building skin that can generate and store energy without requiring electrochemical expertise from architectural designers. By utilizing renewable energy sources, such as solar energy and hydrogen, this system can help to reduce CO₂ emissions and expand renewable energy penetration without concern for damage to the existing grid.

This research provides valuable guidelines for electrochemical applications in buildings and will be further developed in the next phase by constructing a scaled-up custom prototype. An automatic, smart system will be incorporated to introduce water and monitor radiation and gas flow rates. Carbon capture technology may also be added to create a more advanced product. Because this system is intended for building envelopes, a simplified, easily commercialized, and widely used system would be attractive.

In addition to the goals mentioned above, the system's most crucial aspect is achieving optimal energy efficiency conversion. This innovative building skin system can help contribute to a cleaner and more sustainable future by continuously improving and optimizing the technology.

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