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Article

Scale and implementation of the possible solar-hydrogen system for island communities

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ABSTRACT

As technology progresses, there is an increase in possibilities of designing an independent and self-reliant energy source for small communities. Island and remote communities often have to rely on fuel transportation and main grid development for energy supply. By using renewable energy as an alternative choice for energy sources, small communities can remove hazardous emissions while saving money on fuels and shipping costs. Solar-to-Hydrogen (StH) microgrid is a system of solar panels and hydrogen energy systems that can capture and store solar energy for daily usage without fear of energy disruption during nighttime. Despite the initial high capital investment, the concept can be explored and implemented as the long-term economic benefits are present when the cost of electricity is high for remote locations. This study is dedicated to researching and designing a microgrid that can sustain a small community without the presence of 3rd energy source for these communities.

1. Introduction

Since the beginning of the 21st century, renewable energy has become the main topic and focus of global development policies to gradually transform into an alternative source in the event of fossil fuel depletion. Solar energy, geothermal energy, wind energy, tidal energy, and wave energy… have been the notable energy sources to generate electricity in a sustainable and self-reliant manner. As the global population reaches over 8 billion in 2023 and as the life standard continues to increase, the state of energy sufficiency becomes more dramatic and problematic and requires the mass application of renewable energy. Two of the most successful renewable energy sources are solar energy and wind energy. They have been utilized in large-scale industrial and commercial applications. Solar power has the greatest potential of all, with 3×10^{24} MJ of energy released from the sun to Earth's surface annually [1]. Only a very small portion is currently exploited by humans, and there are numerous opportunities along with the development of future technology. In recent years, solar energy has become the answer to energy questions for remote and island areas. These areas, in many cases, do not have access to the main gridlines or do not have the capability to support such infrastructure. Because of this, electricity generation costs are higher in isolated communities, regardless of subsidies from local governments. For example, in 2023, the electricity cost in the mainland United States is \$0.12/kWh, while on the island of Hawaii, it is \$0.40/kWh, four times the mainland cost [2]. Instead of relying on fossil fuels, solar energy can pose as an alternative self-sustaining solution. No transportation of fuel is required, while the emission is eco-friendly. For small and isolated communities, solar power microgrids can be a viable option for long-term energy solutions. A microgrid is a small electrical generating system that can be independent and self-reliant. It ensures a stable and reliable energy source while maintaining a manageable, economical cost for communities. Microgrid design consists of 4 main components: the micro-energy source, the distribution network, the energy storage system (ESS), and the control module [3]. As it is designed to be compact and flexible for locations, it can be grid-connected or totally isolated. The micro-energy source itself can be fully conventional, hybrid renewable, or fully renewable. As the fossil fuel cost continues to rise, accompanied by future carbon taxes, the solar power microgrid offers total independence without the need for ports and logistic infrastructure development for fossil fuel transportation. In one of the studies, Ma et al. confirmed the feasibility of a solar system in combination with wind power for a remote island [4]. Nonetheless, solar power microgrid has some disadvantages. It relies on daytime, geographic conditions, and weather conditions. Solar energy can only be generated during the daytime; this means that the surplus energy is either wasted or needs to be stored somehow to reserve the energy for nighttime. During nighttime, solar energy generation is almost zero, and fossil fuels or backup gridlines have to be used to substitute. Daytime in the summer is also longer than in the winter. This varies the amount of energy generation over the seasons. Different geographic conditions also have negative effects on solar power. The efficiency of power generation increases as the location is closer to the equator as shown in the potential photovoltaic (PV) map Figure 1. Locations such as Hawaii, Guam, or the Virgin Islands will require fewer solar panels with greater output when compared with other locations such as Attu and Nunivak islands. Finally, weather conditions have significant effects on solar power. Cloudy weather over a long period of time will hamper the generation output. That is the reason why an energy storage system is required in the microgrid system. Most of the time, solar power excess is left to be wasted if it cannot be integrated back into the main grid or already exceeds the load capacity. Studies often show the generated energy curve increases gradually during the day, overreaching the required load during mid-day, then gradually decreasing in the afternoon until sunset. In the case of an ESS, when the generated energy curve and usage load have intersected, the excess will be converted and stored so that it can be released when the solar power output can no longer sustain the energy load. This can be nighttime, bad weather days, or a black-out emergency. Current ESS types include the battery model (BESS), the hydrogen model (HESS), and the hybrid model. The hydrogen model (HESS) works by converting the electrical power into hydrogen gas through the process of electrolysis. Hydrogen gas is then compressed and stored in an external tank. When the solar power output can no longer sustain the energy load, hydrogen gas is decompressed and converted back to electricity through fuel cells (FC). Different from BESS, which is constrained by the battery size and number, the hydrogen model is constrained only by its storing capacity. This allows it to be externally expanded until the hydrogen storage capacity overcomes the solar power excess. One of the papers related to the area is Li et al.'s study on the surplus renewable energy source generation on the island of Kyushu, Japan, to decrease the energy curtailment [5]. The solar power curtailment would be converted into a huge amount of hydrogen gas, adding value to the grid-connected solar and wind energy. The model of a solar-hydrogen system (SHS) has been in discussion in the last few decades. Despite the benefits of hydrogen fuel cell systems, their development has been limited due to the extremely high cost of the electrolyzers. The high investment in electrolyzers, in addition to the renewable energy generator, has often caused a reduction in design scale. The hydrogen system itself also has some setbacks in terms of its technology with fuel cells having only around 40-60% efficiency. Hydrogen itself is a highly flammable gas with the chemical characteristics of metal embrittlement when being stored for a long period of time. Making hydrogen even more dangerous is the fact that, unlike a hydrocarbon flame, human senses cannot easily detect a hydrogen flame. People who come upon a hydrogen flame will not see it, even up close. For microgrids, this poses potential problems if careful maintenance and inspection are not performed regularly. Some research has proposed to transport hydrogen gas for external applications, with prices fluctuating at US$5/kg in 2023 [6]. This comes with a loss of self-reliance on the microgrid, with the system having to rely on the main grid at critical hours. Although it can be more economically viable, this leaves out as the solution for remote areas where microgrid is supposed to ease the energy concerns.

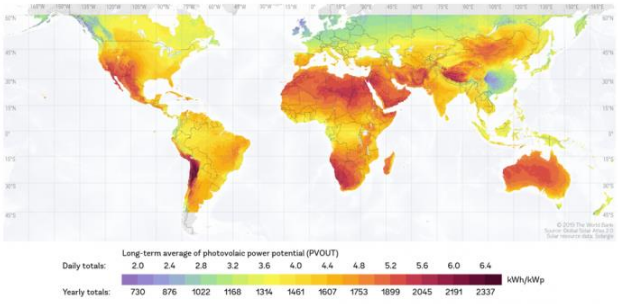


Figure 1. Potential for Solar PV energy according to World Bank Group's Global Solar Atlas [7]

Most studies have called out these problems and have often mentioned the compulsory combination of backup gridlines, fossil fuels, and wind power to substitute for the power drop. However, the current scale has been minimal in terms of the research on the possibility of totally independent microgrid. For example, Shahbazbegian et al. [8] and Nakamura et al. [9] designed power-to-hydrogen systems that still rely on the main grid for the load's substitute. Therefore, this paper dedicates itself to the possible application of an SHS under a totally independent microgrid for remote and island areas. This paper also identifies the optimal model, the size, the cost of installing a hydrogen system, and the economy of such a model. The goal is to understand the economic possibilities of the design for isolated areas.

2. Methodology

2.1 End-user application

For practical purposes, the microgrid is designed to be able to sustain a university hall's electrical load. The test subject is Arkansas Tech University's engineering department, Corley Hall (Figure 2). The building occupies an area of approximately 2,525m^2 or 27,190ft^2 with four parking lots, each with a size of 4,000 m^2. The possible maximum infrastructure area for the model includes the roof area as well as four parking lots with a total area of 16,000m^2. Because Corley has two floors, the generated energy must satisfy the load of a total of 5,050m^2. Since the actual data on the annual electrical usage is unavailable during the study, the value for annual energy usage is based on the national electrical usage data from the U.S. Energy Information Administration (EIA) (see Table 1). According to EIA, an average university consumes over 1.2 million kWh annually. When compared to a small household, this is equivalent to 150 houses or a small community. This can serve as a good reference for isolated and island communities. The study chose solar-to-hydrogen microgrid as the main studied model. The design took into consideration the location of the University as well as comparing it to different locations to calculate the scale and capital cost. Regardless of the location, the minimum energy output must be able to cover the required energy load during the lowest daytime time frame without the need for main gridlines integration. The scale of the power model must fit within the building's precinct and must be optimized for the setup, maintenance, and sustaining. The total electricity consumed by the building is calculated through equation (1), in which the area and the power density are provided.

$$E_{\text{daily load}} = A_{\text{total}} \cdot \frac{S}{t} \quad (1)$$

where $E_{\text{daily load}}$ is total energy consumption in a day, A_{total} is the total area of all surface floors in the building, S is the power density or the average consumed power per square foot ($\frac{\text{kWh}}{\text{m}^2 * \text{yr}}$), and t is the time, which, in this case, is 365 days.

Figure 2. Arkansas Tech University's engineering department [10]

Table 1. Annual electricity consumption totals [11, 12]

	per building (thousand kWh)	Average size (Thousand ft^2)	Average per square foot (kWh)	Median per square foot (kWh)
Education	345	31.5	11.0	8.7
College or university	1,202	69.2	17.4	14.4
Small Household	8	1.4	5.4	-
Average house	10	2	5.4	-

2.2 Testing Model

The model in this study is a solar-to-hydrogen system (StH), as shown in Figure 3. Solar power from the sun is converted to electrical energy through a photovoltaic panel (PV panel). The solar power gradually increases during daytime, peaks during midday, and decreases as nighttime approaches. As it increases, the solar power energy level passes the demand load, where most of the energy excess is wasted. In the microgrid system, the excess energy is transferred to the battery and then to the electrolyzer to convert electrical energy into hydrogen gas for storage. As Hydrogen gas is generated through an electrolyzer, it is compressed and transferred into a storage tank where it is kept until needed. When solar power decreases below the demand load, the battery kicks in as a temporary energy source. After the battery's energy level decreases under a certain percentage, the fuel cell kicks in and supplies the load demand until the next solar power cycle. Parra et al. show that photovoltaic power is generated effectively from 9 a.m. to 5 p.m. during a high-output day [13]. During that time, electrolyzers began to convert excess electricity to hydrogen at the rate of 65-70% of the electrical power received from the PV panels. Electrolyzers' gas is depleted at around 4 p.m. as the photovoltaic power decreases. At the same time, the Hydrogen gas was pumped from the storage tank to fuel cells to generate electricity and continue so after the PV panels were off. Li et al. [14] show the electrolyzers' output peaked between 12 p.m. and 2 p.m., while fuel cells' output remained constant after 7 p.m. in one of the models. Due to efficiency during hydrogen conversion as well as covering the real-time demand load, the energy produced by solar PV must be higher than electrolyzers while the energy produced by the FCs must be lower than electrolyzers. Figure 4 shows the representation of energy level of PV, electrolyzers, and FCs throughout the day if the testing model was to be put into operation.

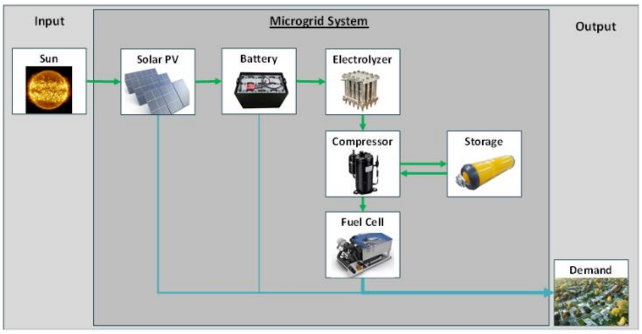


Figure 3. Microgrid system schematic

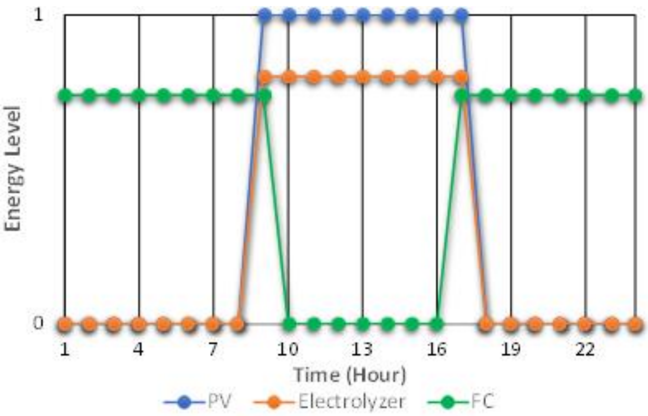


Figure 4. Desired energy level vs. time of microgrid's energy source

2.3 Photovoltaic panel (PV panel)

For the microgrid to operate independently and without relying on a 2nd energy source, the energy generated by solar power must be equivalent to or higher than the demand load or $E_{PV} \geq E_{load}$. However, Figure 4 indicates that since the time to generate solar power is limited according to daytime, the energy rate or power of the PV must be much higher than the demand load so it can generate enough excess energy to store for nighttime or equation (2). The power generated by PV panels or daily energy is calculated from the product of solar insolation SI ($\frac{kWh}{m^2 . day}$), the available surface area $A_{surface}$ (m^2) and the efficiency of commercial solar panels, equation (3).

$$P_{\text{PV}} \gg P_{\text{load}} \quad (2)$$

$$E_{\text{PV}} = \text{SI} \ . \ A_{\text{surface}} \ . \ \eta \quad (3)$$

The solar insolation SI is generated by measuring the solar radiation in a set period of time. As it is measured, each location, depending on the latitude difference and seasons, has a distinguishing value. Figure 5 shows the average solar energy per square meter that any location within Arkansas might receive in a day. Figure 5 also shows the variation in SI between different months. As seasons change, SI values peak during summer and plummet during the winter. The SI values are also different when being compared at different latitudes and different climates. Figure 6. shows the lowest average SI values in different states of the United States territory. States that are closer to the South and near the equator have higher SI values as well as the most stable trends. The top state is Hawaii, with the lowest value at 3.83 kWh/m^2 per day during December and the highest value of 6.6 kWh/m^2 per day during June and July. In order to design a model that can sustain and operate fully independently, the minimum values for SI are used to calculate the generated energy of PV panels based on a hypothetical area. The obtained values are then compared to total energy consumption in a day $E_{\text{daily load}}$ in order to determine the correct scale of the solar panels' area. The goal is to have a sufficient amount of energy during daytime use and to store it for nighttime use. The efficiency of most current solar panels varies between 17% and 20% [16]. However, research has shown that efficiency can reach the range of 30% in some studies [17]. For this study, the PV efficiency is set at 20%.

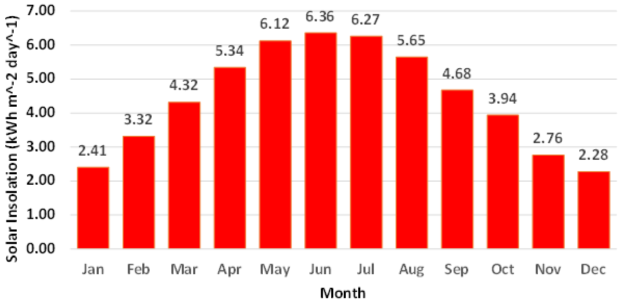


Figure 5. Average solar insolation of Arkansas throughout a year [15]

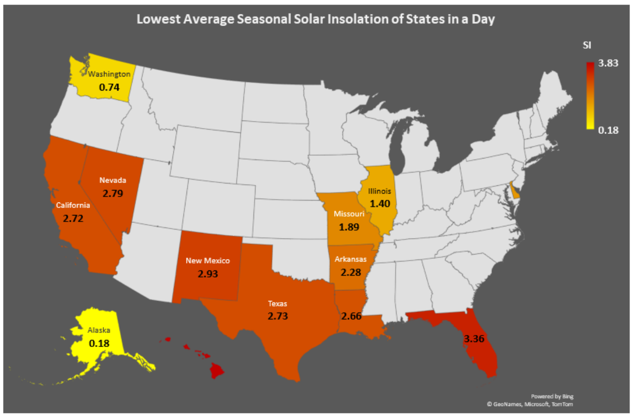


Figure 6. Lowest average seasonal solar insolation of states in a day [15]

2.4 Battery system and model

The BES has been a subject undergoing intense study and discussions for usage in a microgrid system. BES is the traditional method for storing backup energy in an electricity circuit and has high reliability in power transition during energy switch [18]. Before HES, BES was the default standard for storing electrical energy from gas turbines, fossil fuel engines, and renewable sources. For small independent and island grids where the load is under 5-200MW, BES has been very effective in providing and maintaining electricity service [19]. BES stores energy through an electrochemical process where the chemicals are contained inside the battery to absorb the energy. Some batteries have an instantaneous response time of about 20ms, which allows them to adapt quickly to any situation [20]. When a high load is required in the grid, and the battery is no longer charged, the battery releases the energy back into the system, maintaining the gridline's operation. BES maintains uninterrupted and stable power flow to the gridlines as long as there is still power stored in the chemical. When the system observes a sudden peak in energy usage in the microgrid, the BES enables flexibility for the system without the risk of blackout. Despite its advantages, the battery itself has some minor setbacks. As it stores energy within its chemical, when storing capacity is reached, excess energy generated from the renewable energy source has to be wasted. In order to increase the BES capacity, another battery must be installed. This increases both the complexity of integrating the system as well as the required space for the battery itself. Even though the battery can discharge 90-100% of its energy, frequent charge and recharge cycles reduce its lifespan significantly. Hlal et al. [21] studied the optimum battery depth of discharge of off-grid solar PV and stated that the range is between 20% and 70% to maximize the life cycle of BES. Alramlawi et al. [22] claimed that when comparing the battery lifespan of the dept of charge between 40% and 90%, there is a decrease of more than 25% or 15,000h in lifespan. Unlike BES, HES allows more capacity in energy storage since it stores its energy externally in the form of hydrogen gas. This allows the microgrid to expand its capacity by installing more storage tanks for hydrogen in case of excess energy without increasing the complexity of the electrical integrating system. However, FC in HES has a relatively slow response time in comparison with the traditional battery. Sun et al. [23] tested the PEMFC under multiple conditions of temperature, pressure, anode, and cathode humidification and showed that FCs could take anywhere from 2 minutes to half an hour in order to reach their capacity and stabilize the released power. In actual application, this can lead to sudden power drops and blackouts if the microgrid only relies on HES to supply the energy. Sudden changes in demand load and short-term loss in PV power put extreme stress on FCs as well as ELs. In a cloudy day, both FCs and ELs have to turn on and off continuously over a long period of time, degrading their lifespan. Therefore, a battery is needed in the microgrid in junction with the HES, so the power supply is always stable and uninterrupted. One of the most optimal setups is the battery-concentrated system, which charges and releases the battery first before HES. When BES is charged over 60-70%, energy is transferred into ELs where it is converted to hydrogen gas. When BES is depleted under 50%, FCs start to convert hydrogen back to electricity for long-term usage. Figure 7 illustrates how the BES-HES system can operate. Kafetzis et al. [24] proposed the start of FC cycles at the 20% limit and Els at the >70% limit of the battery's SOC in a battery-concentrated-hydrogen system. The study also mentions that the FC should be utilized to maintain the battery's SOC at 50% whenever its SOC reaches the lower limit to ensure safe operation. Rey et al studied how the battery-concentrated system could outlast the HES-concentrated system [25]. They concluded that the HES-concentrated system would cost 3 times more in investment while requiring a replacement of 3 ELs and 8 FCs in the course of 20 years. The BES-concentrated system would only require a replacement of 1 battery bank and 1 EL in the same condition. The BES system is only responsible for supplying short-term energy during the transition state (~30 minutes) or during a sudden power surge. This is considered the most efficient metrology to utilize the HES while optimizing the best lifespan of the system.

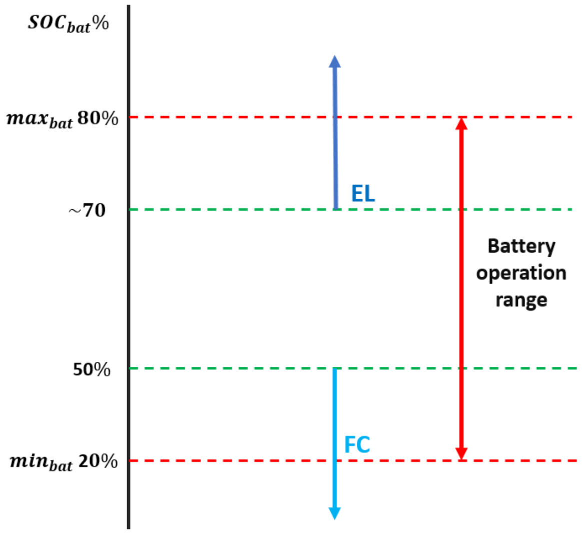


Figure 7. Possible setting for Battery SOC in junction with EL and FC cycle

2.5 Electrolyzers

There are currently 2 common types of electrolyzers widely utilized for commercial applications: Alkaline electrolyzers and Proton-exchange membrane electrolyzers. Their compact size and relatively low maintenance cost are the main reasons and focus for the integration of HES in microgrid development. In order to decide which electrolyzer to use, 2 things are taken into account: the ROI cost and the lifespan of the system. ROI cost must be achieved within the lifespan of the system in order for the model to be successfully implemented. Alkaline electrolyzer (AEC) is currently one of the three most common electrolysis processes, in which water is split into hydrogen gas for commercial or industrial usage. It is also the oldest electrolysis method, dated back to the 1800s [26] AEC consists of a cathode, an anode, a separator, and an alkaline electrolyte solution. KOH or Potassium Hydroxide is currently the most common solution for AECs, other than NaOH or Sodium Hydroxide. The process requires electricity as an input of energy and releases heat as a byproduct. The AEC operates at around 60- 80°C and 1.8-2.4V of terminal cell voltage with an efficiency of around 62-82% [27, 28]. For every kWh of electrical energy, AEC produces around 0.019 kg of hydrogen gas [29]. The cost of an AEC varies from around $250-400 per kW, which is cheaper than a PEMEC electrolyzer [30]. It also accepts high tolerance for impurities and dust in the feedstock. Since its components are widely available, it does not depend on the noble metal catalyst like other electrolyzers [31]. In contrast, it is less efficient than PEMEC and requires higher operating pressure [32]. AEC generally has a lifetime of 60,000- 90,000 hours or around 8 years. However, due to its alkaline nature, it is more prone to oxidization and corrosion, which can reduce its lifespan to below its standard time. It also can take up to 50 minutes for the AEC to be in full operation mode, while the PEMEC only takes 5 minutes [33]. Evolving from the AEC, the proton-exchange membrane electrolyzer (PEMEC) uses solid polysulfonated membranes as both a separator and a gateway for ions. The membranes have better gas permeability, productivity, and pressure characteristics and require lower thickness. This allows PEMEC electrolyzer systems to be more compact while producing pure hydrogen gas at higher rates than others. For every kWh of electrical energy, PEMEC produces around 0.021 kg of hydrogen gas [34]. As a result, PEMECs have become more favorable for pure hydrogen generation. PEMEC's operating temperature is the same as AEC at around 60- 80°C [35]. PEMEC's efficiency varies between 70% and 80%, with a study showing a possibility of 94% [35, 36]. Despite its higher efficiency, the PEMEC structure requires the usage of noble metals like Platinum, Iridium, and Ruthenium. Currently, platinum is considered the state-of-the-art electrocatalyst for the PEMEC cathode [37]. As these materials are rare and precious metals, the cost of the PEMEC is significantly increased. The current cost is $500-1100 per kW, and a single PEMEC costs around $400,000- $870,000. Its lifespan is also less than AEC, with the durability at around 30,000h -40,000 [38]. This can be traced to PEMEC's higher efficiency, purity, and ability to produce hydrogen under higher pressure, which is attributed to its fast degradation [39]. In order to calculate the amount of hydrogen gas produced by the electrolyzer, the Gibbs free energy ΔG_d^0 is used to represent the electrical power required to break the O-H bonds and generate the hydrogen molecules. The electrolysis process is represented by equation 4.

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{4}$$

$$\Delta H_d^0(H_2O(l)) = \ +285{,}840\,\frac{kJ}{kmol} \tag{5}$$

$$\Delta S_d^0(H_2O(l)) = 163.150\,\frac{kJ}{kmol\ K} \tag{6}$$

$$\Delta G_d^0(water) = \Delta H_d^0 - T\Delta S_d^0 \tag{7}$$

where ΔH_d^0 is the enthalpy, ΔS_d^0 is entropy, and T represents the operating temperature of the electrolyzer. The unit of ΔG_d^0 is under J/mol, so it needs to be converted to kg of hydrogen gas. ΔG_d^0 is divided to $M_{H2} = 2$ kg/kmol to obtain the unit J/g or kJ/kg as 1 mol of hydrogen gas equals to 2 g hydrogen gas. The full equation to get mass of hydrogen from PV's energy is represented by equation 8, where 1kJ= 2.87×10^{-4} kWh and η is the efficiency of the electrolyzer.

$$\mathcal{M}_{H2} = \frac{\eta_{EC}(E_{PV})(M_{H2})}{\Delta G_d^0} \quad \frac{1}{2.87\times10^{-4}} \tag{8}$$

For PEMEC with $\eta = 0.7$ and operating temperature of 60°C, the simplified equation is:

$$\mathcal{M}_{H2} = \frac{E_{PV}}{47.46} \tag{9}$$

For AEC with $\eta = 0.62$ and operating temperature of 60°C, the simplified equation is:

$$\mathcal{M}_{H2} = \frac{E_{PV}}{53.58} \tag{10}$$

Both 47.46 kWh/kg and 53.58 kWh/kg can be validated using the previously mentioned ratio of mass and electrical power.

2.6 Fuel Cells (FC)

Current technology has propelled the fuel cell system to be widely used in portable and stationary applications. While having the same reverse characteristics as the electrolyzer, the proton membrane fuel cell (PEMFC) has seen greater advancement in comparison with the alkaline fuel cell (AFC). Despite its reliability, AFC has a very low lifetime, measured between 3,000-5,000 hours or around 1 year, due to the voltage degradation of the individual cells [40]. The main cause of degradation is due to the corrosion by CO_2 where CO_2 reacts with free OH- ions to form carbonate $CO3^{2-}$ ions and reacts with Potassium in its electrolyte to form salt [41]. This reduces the available electrolyte KOH within the FC with the rate proportional to current density. Hence, the durability of the AEC degrades over a short period of time. Although the AFC has a relatively affordable cost of $400-$600 per kW, it is not considered in this study [42]. On the other hand, PEMFC has passed the demonstration phase and has been successfully applied in commercial vehicles and backup power applications. PEMFC uses perfluorosulfonic acid membranes in its design to allow hydrogen ions to flow to the cathode of the FC. It is considered to be low-temperature FCs that operate around 50-80°C [43]. As the temperature, FC loses its efficiency as the energy release is inversely proportional to temperature. Due to PEMFC's wide application and design, its efficiency has a wide range between 40% and 80% [44, 45]. Parra et al. [46] designed a community hydrogen storage system for end-user applications and stated that the efficiency of PEMFC is 79%. For this study, the efficiency of PEMFC is set at 60%. The current cost of PEMFC has fluctuated a lot based on the countries and the providers. In the U.S., the price is about $700 per kW [47]. The lifetime of PEMFC has somewhat influenced its popularity in research and development. It is targeted to last around 60,000-90,000 hours or 8-10 years for steady-state operation [48]. However, PEMFC has some minor setbacks. Although PEMFC can provide stable electrical power for the microgrid, its response time can be too long to avoid a brief blackout during the transition period. Cheng et al. investigated the PEMFC dynamic response and affirmed that it takes about 25 seconds for the power of PEMFC to rise from 10 kW to 110 kW [49]. In order to counter this setback, the BES system, therefore, has a decisive role in the microgrid, ensuring a smooth transition between energy modes. The fuel cell process is presented by equation 11. The electrical power generated by an FC system is due to the changes in the Gibbs free energy of formation ΔG_f between the products and the reactants. The theoretical energy generated by a fuel cell has a value close to 33 kWh/kg under 100% efficiency which matches with reference [50].

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{11}$$

$$\Delta G_f = \Delta G_{H2O(l)} - \Delta G_{H2(g)} - \Delta G_{O2(g)} \tag{12}$$

where at the temperature of 50°C

$$\Delta G_{H2O(l)} = -308{,}464 \frac{kJ}{kmol},$$

$$\Delta G_{H2(g)} = -42{,}180 \frac{kJ}{kmol}, \quad \Delta G_{O2(g)} = -33{,}130 \frac{kJ}{mol}$$

$$E_{FC} = \mathcal{M}_{H2} \frac{\Delta G_f}{M_{H2}} (2.87 \times 10^{-4})\eta \tag{13}$$

For PEMFC with η=0.6 and operating temperature of 50°C, the simplified equation in kWh is:

$$E_{FC} = 20.07(\mathcal{M}_{H2}) \tag{14}$$

3. Results and discussion

The total power consumption of the Corley building is approximately 2,590 kWh/day. The total roof area of the Corley building is 2,525m^2, which can generate a maximum average of 2570 kWh using equation 3 under the condition that 80% of the area can be utilized. This figure, however, is insufficient to allow the microgrid to be self-reliant or sustain the power grid during the majority of the year. Figure 8 shows the generated power and the power deficit of the PV grid. The power deficit decreases during the summer months when solar radiation is higher. Nonetheless, during winter months, the available solar power can only supply 35-40% of the load. Therefore, the roof-top PV is not sufficient to sustain the building's energy usage.

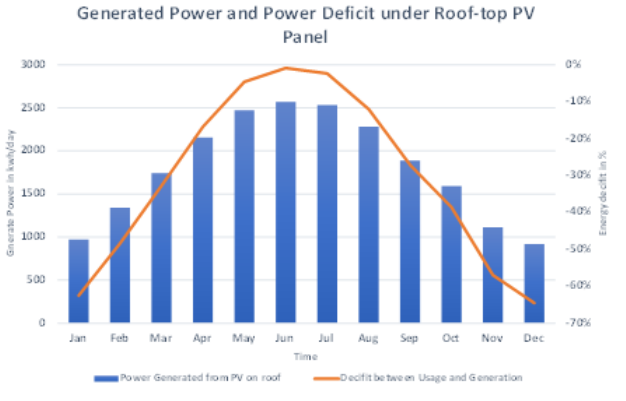
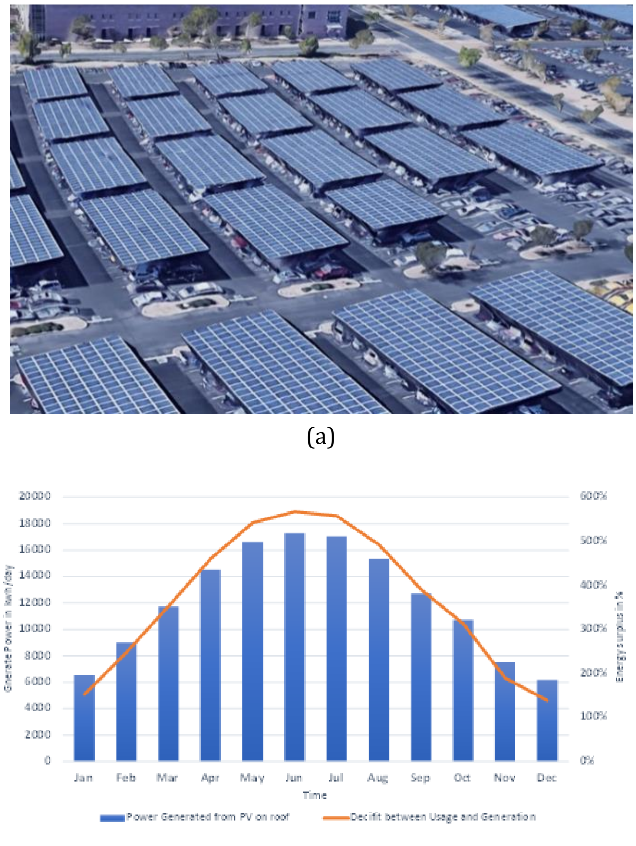


Figure 8. Generated power and power deficit under roof-top PV panel

The alternative is to utilize the four parking lots with a total area of 16,000m^2 instead to see if the generated power from the parking lots can fulfill the required energy load. The model for the installation of PV panels is based on parking lots of the Intel semiconductor factory in Phoenix, Arizona, which combines the solar panel as the roof for parking spots. The PV panel generates solar power as well as provides shading areas for vehicles, as in Figure 9a. If 85% of the area is able to be utilized, the PV grids might see a significant surplus in energy during operation.



(a)

(b)

Figure 9. a) Solar PV roof parking lot and b) Generated power and power deficit under solar PV roof parking lot

According to Figure 10, even in the lowest month of solar radiation, the microgrid would see a generation of 6,188 kWh, a surplus of 3596 kWh in comparison with the power consumption of 139%. This surplus covers HES loss during the EtH conversion as well as the HtE conversion. Using the data of load profile for a typical college building in California, a proportional dataset can be generated to simulate the actual load at Arkansas Tech University during the day [51]. In order to define the minimum capacity of the hydrogen tank, its mass needs to be calculated from the surplus of the PV power. The average surplus can be calculated by subtracting the demand load from the generated PV power at the same hour. Figure 10 shows the effective sun hour per day in each month in Arkansas. During December, the number of effective sunlight hours is only 3.5 hours, according to NREL [52]. As a result, the amount of needed hydrogen for the rest of the day must be generated in that 3.5-hour frame when the PV energy generation is maximized. Figure 11 shows the required power generation during the 3.5 hours and the estimated power consumption during the day (total consumption is 2590 kWh). The comprehensive amount of electrical energy to be converted to hydrogen gas after subtracting it from the consumed energy is 5,575 kWh or 90% of the generated PV energy. Using equation (9), the amount of equivalent hydrogen mass using the PEMEC is 117 kg. For the AEC, the amount of equivalent hydrogen mass is 104 kg using equation 10. The hydrogen storage tank that the microgrid needs lies between 120 kg and 150 kg for the minimum value, where the extra capacity can be used as seasonal or weather backup.

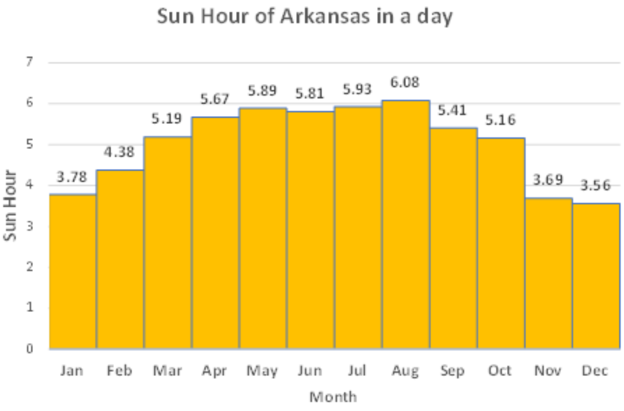


Figure 10. Effective sun hour per day vs. month of Arkansas [52]

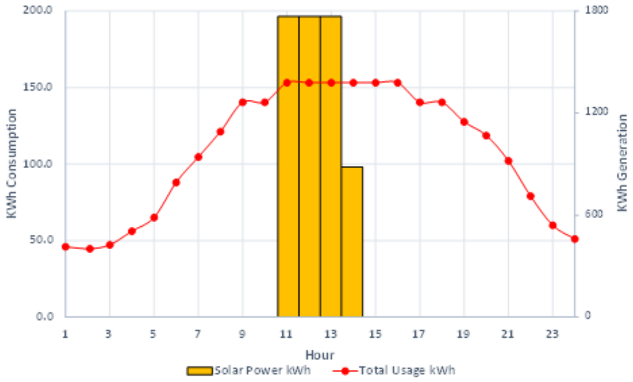
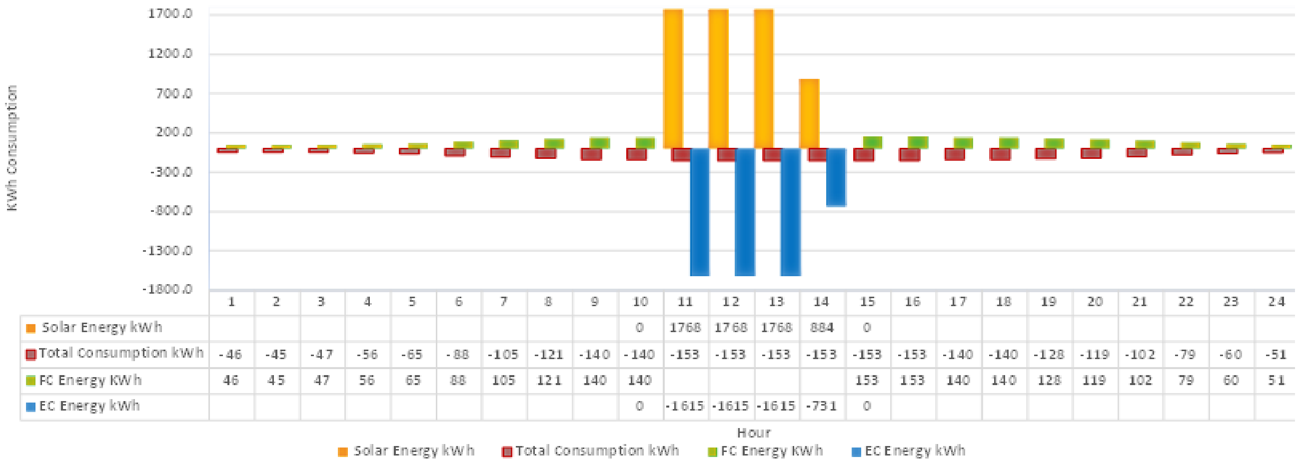


Figure 11. Total energy usage and generated solar power vs. hour in a day in December

When sunlight is no longer available, FCs kick in to convert the hydrogen gas back to electricity. Using equation 14, the amount of equivalent electricity in a PEMEC-PEMFC is 2348 kWh. In the AEC-PEMFC, the generated electricity is 2087 kWh. The possible total amount of electricity supplied by the microgrid is 2960 kWh and 2700 kWh for PEMEC-PEMFC and AEC-PEMFC, respectively. This amount of energy is sufficient for the microgrid to be independent during the lowest sunlight month of December. Figure 12 shows the estimated model for the energy cycle within the microgrid. In order for the microgrid to be implemented in actual applications, its ROI must outweigh its cost during its lifespan. Therefore, it is necessary to generate the balance sheet for 30 years. For every 10 years, both the EC and FC are required to be replaced due to their lifespan degradation. The estimation for total cost (excluding battery and grid components) is shown in Tables 2 and Table 3. The PV panels cost about $3,060 per kW and are the most expensive investment in the microgrid due to their scale [53].



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
■ Solar Energy kWh										0	1768	1768	1768	884	0									
■ Total Consumption kWh	-46	-45	-47	-56	-65	-88	-105	-121	-140	-140	-153	-153	-153	-153	-153	-153	-140	-140	-128	-119	-102	-79	-60	-51
■ FC Energy KWh	46	45	47	56	65	88	105	121	140	140					153	153	140	140	128	119	102	79	60	51
■ EC Energy kWh										0	-1615	-1615	-1615	-731	0									

Figure 12. Total energy usage and generated solar power vs. hour in a day in December

The Hydrogen tank with compressed pressure costs around \$400-\$700 per kg of hydrogen gas and is the least costly spending [54]. The total capital spending is then compared with different electrical costs from different locations, as in Table 4. Arkansas, which is located within the mainland United States, has a fairly low cost of energy at \$0.12 per kWh in 2023 [55]. In contrast, Martinique Island of France, which is located in the Caribbean Sea, has a high cost of \$1.14 per kWh [56]. Small islands with small populations tend to not afford to build and maintain large power plants and therefore, have higher rates of electricity. The island of Cook and Solomon (island countries), which has less than 1 million inhabitants, have rates around \$0.52-\$0.69 per kWh. The cost of electricity of each location is multiplied by the total power consumption of Corley building of 945,350 kWh/year (2,590 kWh/day *365 days), then added up over the course of 30 years to determine if and when the spending savings across the capital spending. Figure 13 and Figure 14 show the spending vs capital spending of 2 microgrid models. For both graphs, when the cost is below \$0.30 per kWh, the microgrid economy is unable to sustain itself under a 10-year EC-FC replacement schedule within 30 years. As the PEMEC lifespan is only 4-6 years, it must be replaced, and its cost must be added to every 7th year. Hydrogen tank, AEC, and PEMFC also need to be replaced every 10 years; therefore, the capital cost rises every 6-10 years, depending on the model of the microgrid. 30 years also marks the lifespan of the solar panel to be replaced as its efficiency has decreased to no longer fit to generate electricity [57- 59]. When the cost is above \$0.50 per kWh, the spending saving crosses the capital investment within 15 years for the AEC microgrid while it takes 30 years for the PEMEC microgrid. When the cost is above \$1.00 per kWh, the spending saving crosses the capital investment within 6-9 years. The choice of AEC microgrid and PEMEC microgrid lies solely upon the communities based on their financial capability and requirements. For most locations with costs under \$0.50 per kWh, such as Guam and Hawaii, the PV-AEC-PEMFC microgrid might be more suitable as it is significantly cheaper due to the AEC cost. The ROI might be achieved within 20 years for these locations.

Table 2. The capital spending of PV-PEMEC-PEMFC microgrid

Component	Cost per KW/ Cost per kg H_2	Total Capacity in kW or kg H_2	Total Capital Spending in US\$	Lifespan (years)
PEMEC	1,100.00	1,614.00	1,775,400.00	4-6
Hydrogen tank (kg)	700.00	117.00	81,900.00	10
PEMFC	600.00	153.00	91,800.00	8-10
PV	3,060.00	1,768.00	5,410,080.00	30
Total			7,359,180.00	

Table 3. The capital spending of PV-AEC-PEMFC microgrid

Component	Cost per KW/ Cost per kg H_2	Total Capacity in kWh or kg H_2	Total Capital Spending in US\$	Lifespan (years)
AEC	400.00	1,614.00	645,600.00	8-10
Hydrogen tank (kg)	700.00	117.00	81,900.00	10
PEMFC	600.00	153.00	91,800.00	8-10
PV	3,060.00	1,768.00	5,410,080.00	30
Total			6,229,380.00	

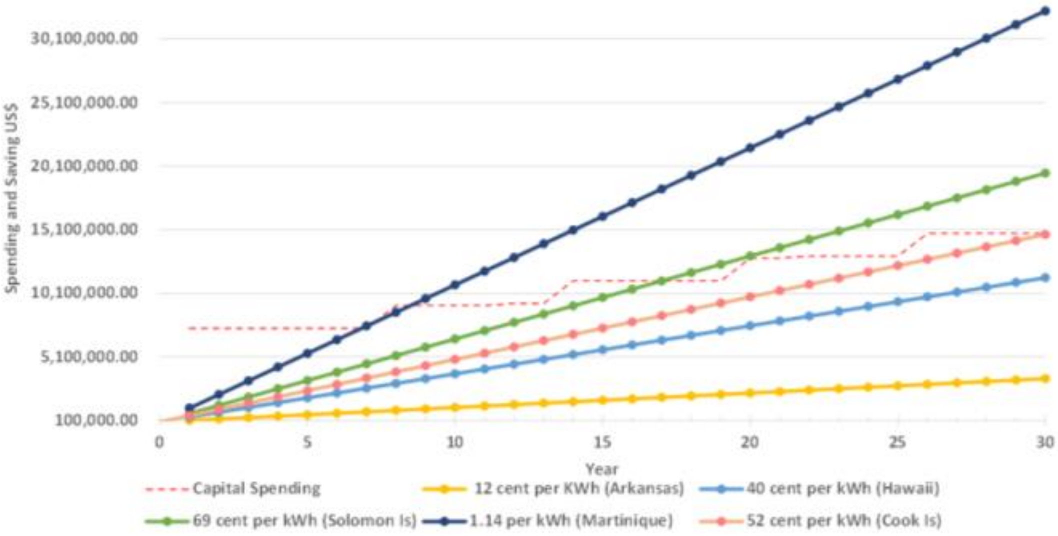


Figure 13. Saving and capital spending over 30 years of PV-PEMEC-PEMFC Microgrid

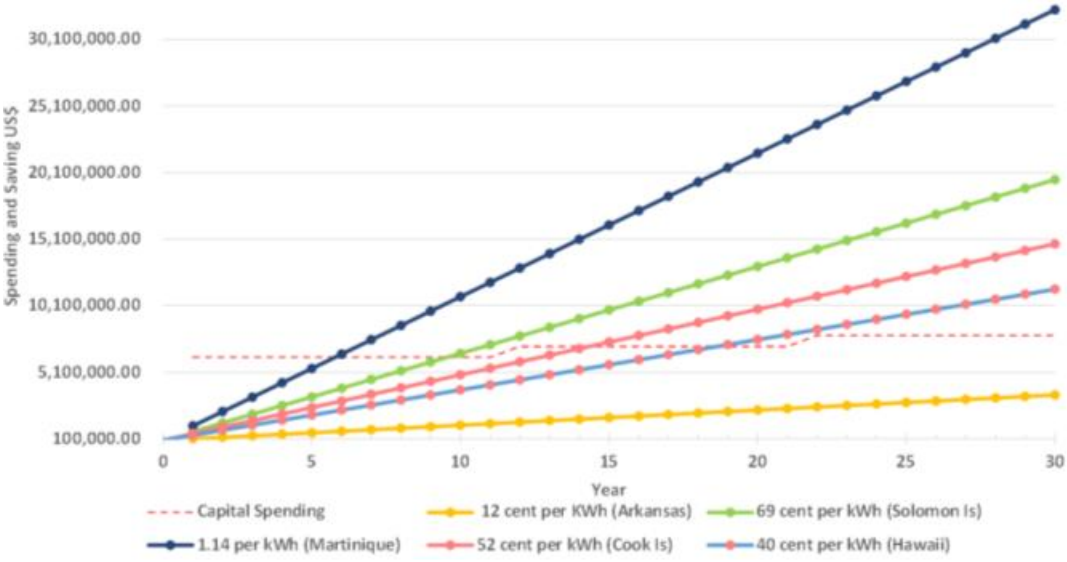


Figure 14. Saving and Capital Spending over 30 years of PV-AEC-PEMFC Microgrid

4. Conclusion

This paper proposed a design to build a microgrid for small communities in remote and island areas based on the high-power consumption of a university building in Arkansas. This microgrid uses 100% renewable energy without the reliance on fossil fuels and other means of energy sources. The StH microgrid consists of PV panels and an HES system which converts excess solar energy to compressible matter during the daytime and releases electrical energy during nighttime. The lifespan and the economic feasibility are then established and compared to understand the impact of such a system in the communities. The expectation was that the microgrid would eventually relieve communities of energy constraints as well as the economic burden in the long-term plan.

- One of the major conditions for an independent microgrid is the location of the application and the availability of space in the area. Location has a crucial role in determining the scale of the system and the economic cost of the project. The investment of PV panels is more expensive than other investments due to its complex system and its sheer scale in order to generate energy. To generate enough power for small communities or commercial hubs, an area of equivalent PV power might be 1.5-4 times the floor area of the load demand. For this study, the ratio was 3.2 times the floor area of the Corley building in order to generate enough power for the HES system, Different locations with different climates and latitudes receive distinguished amounts of solar radiation throughout the year. In turn, the microgrid requires different areas of PV panels to ensure sufficient power to the grid. For example, due to its location and climate, Hawaii receives more sun hours and more solar radiation per meter square than Arkansas throughout the year. The fluctuation means that the required PV power area of Hawaii is less than Arkansas and costs less than Arkansas; therefore, the economic wise favors areas closer to the equators. This poses a great challenge in standardizing capital spending and forecasting accurate models for PV generators.

- Two different kinds of microgrids are established and compared based on their lifespan and their economic feasibility: the PV-PEMEC-PEMFC microgrid and the PV-AEC-PEMFC microgrid. The PV-AEC-PEMFC microgrid has a longer lifespan as well as lower initial capital cost than the alternative, which is suitable for most locations. For the ROI, the cost of electricity at the local locations has a major impact on the possibility of regaining the investment budget or gaining additional income. For areas where the electrical cost per kWh is below \$0.30 -\$0.40 per kWh, the spending saving might not overcome the capital spending in a 30-year period. This is also due to the increase of capital spending every 6-10 years for hydrogen tanks, electrolyzers, and fuel cells due to their efficiency and safety degradation over time. For areas where the electrical cost per kWh is above \$0.40 per kWh like Hawaii and Guam, the spending savings might be able to pay off within a 25-year period under the PV-AEC-PEMFC microgrid. Meanwhile, for the areas that are above \$1.00 per kWh, the additional income is within 10 years.
- This study did not include the BES system as it is a low-capacity system that is only required for transition purposes and only holds 150 kWh in a maximum 0.5-to-1-hour period. The cost of such a system is relatively cheap (~\$150 per kWh) in comparison with the HES system. However, the study recognizes the necessity of the BES system in the case of fluctuation in PV power out and short-term blackouts. The application of BES also increases the lifespan of HES systems while decreasing the number of charging and discharge cycles of electrolyzers and fuel cells in daily operations. In the case of a major power surge in the grid, it is favored that the battery system takes up the stress instead of the HES system to reduce the damage and replacement cost it might cause to the microgrid system.
- Future development will be able to reduce the cost and increase the lifespan of both the PV panels and HES system so that it is more economically viable to mass implement microgrids for more communities. The reduction in manufacturing PV panels and electrolyzers, in particular, PEMEC, will have a determining impact on the microgrid market. PEMEC has some unique characteristics in producing higher hydrogen purity and higher efficiency while limiting the corrosion problem that is observed in the alkaline electrolyte. Current progress has shown that PEMEC efficiency can achieve an efficiency of 80%. Along with the improvement of PEMFC, this will result in lower required PV panel areas and a reduction in capital cost.

Ethical issue

The author is aware of and complies with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The author declares no potential conflict of interest.

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