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Article

Open-Source DC-DC Converter Enabling Direct Integration of Solar Photovoltaics with Anion Exchange Membrane Electrolyzer for Green Hydrogen Production

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Abstract: Fully sustainable hydrogen production demands renewable energy sources. This study uses an approach that combines solar photovoltaic (PV) systems with minimal batteries to tailor the energy supply to the unique demands of anion exchange membrane (AEM) electrolyzers. An open source DC-DC adjustable converter is designed, prototyped, and tested to enable an AEM to operate at its optimum efficiency without disrupting the continuous operation of existing loads. A structured operating schedule is simulated to align PV performance with AEM electrolyzer characteristics. The results show the >90% efficiency open-source converter was able to directly power the electrolyzer while taking advantage of solar energy surplus for hydrogen production. By strategically scheduling the electrolyzer to maximize output and minimize waste the system only utilizes excess solar energy. By employing this sustainable method, the study highlights a scalable solution that not only enhances the efficiency of hydrogen production, but also promotes the deployment of PV.

Keywords: hydrogen; AEM electrolyzer; anion exchange membrane electrolyzer; photovoltaic; green hydrogen; DC-DC converter

1. Introduction

Hydrogen fuel has generated substantial recent interest in the scientific community because of the need for sustainable fossil fuel substitutes. In particular 'green hydrogen' that is produced via electrolysis using renewable energy sources has made substantial progress (Kojima et al., 2023; Oliveira et al., 2021). Although only 5% of hydrogen is currently generated from the electrolysis process, it is expected to increase to 25% by 2050 (Shiva Kumar and Lim, 2022; Wang et al., 2022). Despite a promising path for energy storage and carbon neutrality, integration of hydrogen (H₂) production with the existing power grid still remains inefficient when compared directly with contemporary battery storage technologies, especially considering recent improvements in lithium battery systems (Pellow et al., 2015; Vidas and Castro, 2021). One promising approach to reduce green hydrogen costs is using surplus power from solar photovoltaic (PV) systems that exceeds immediate energy demands (Al-Buraiki and Al-Sharafi, 2022; Ural and Gencoglu, 2014). This approach has the advantage of utilizing renewable energy more effectively, but also avoids some of the limitations associated with grid dependency like energy transmission losses (Energy.gov, 2022), grid congestion, inequitable compensation for solar generators (Schelly et al., 2017; Prehoda et al., 2019) and the variability in grid electricity prices (Kirk, 2022).

In order to achieve fully renewable H₂ production it is necessary to establish comprehensive setups which not only utilize PV power efficiently, but also integrate it with electrolyzer technologies (Song et al., 2022). AEM electrolyzer represent the most promising approach to electrolysis due to their potential for higher efficiency (Falcão, 2023). Optimizing PV systems and batteries specifically

for AEM technology, however, requires detailed discussion and analysis to tailor the energy supply to the unique demands of these electrolyzer (Khalilnejad et al., 2016). Implementing a structured operating schedule to maximize energy efficiency and H₂ output is fundamental for practical application of these technologies (Song et al., 2022), including optimization of the PV system's performance to align with the operational characteristics of AEM electrolyzer (Falcão, 2023; IRENA, 2020). Despite this potential, the literature that focuses on direct use of PV power from DC bus for electrolysis remains sparse, with very few studies detailing the entire setup of such systems (De Lorenzo et al., 2022; Guilbert and Vitale, 2020).

Within this research area, DC-DC converters are essential components for directly DC bus connected PV-powered hydrogen production, but are only commercially available from a few companies that offer custom solutions (Absopulse Electronics Ltd, 2024; "Elejoy," 2024; "Mean Well," 2024). There are studies on open-source adjustable DC-DC converters, but they are limited to low-power, laboratory-scale models that utilize dSPACE processor-based control systems (Brunoro and Vieira, 1999; Koch et al., 2022). Online resources provide guides for constructing low-power buck converters using direct integrated circuits (ICs) (alayi, 2024; Podlesnyi, 2024), which are only suitable for low power devices and not programmable. Similarly, commercially available adjustable DC-DC converters are often based on a non-programmable IC (Drok, 2024). These limitations explain why traditional electrolysis setups, rely on relatively inefficient AC-DC converters, which introduces additional stages of energy conversion and leads to increased losses and costs (Starke et al., 2008). Thus, one approach to overcome this challenge is the development of a low-cost DC-DC converter, which is a crucial step towards efficiency improvement of electrolytic hydrogen production systems. Previous work has shown an effective method to decrease costs for such components is to use an open hardware design methodology (Oberloier and Pearce, 2018; Pearce, 2020). Due to unavailability and poor access to DC-DC adjustable converters in both the market and the open-source community, this work develops a customizable step-down converter is a DC-to-DC converter (buck converter). Current and voltage controls are integrated using an Arduino microcontroller. Despite the availability of some commercial options with inadequate voltage regulation and lacking constant current-constant voltage (CC-CV) control, this project aims to create an open-source solution that fills the existing void, particularly for applications that require more robust capabilities, like running an anion exchange membrane (AEM) electrolyzer.

Filling these knowledge gaps, this study introduces a comprehensive renewable H₂ production setup combined by a structured operating schedule to align PV performance with AEM electrolyzer characteristics. First an open-source DC-DC adjustable converter is designed, prototyped, and tested to enable the AEM to operate at its optimum efficiency without disrupting the continuous operation of existing loads. Predicting realistic and reliable H₂ production rates at daily, monthly, and yearly scale is needed to provide a clear understanding of operational efficacy and sustainability of such systems. Thus, this hardware is combined by a structured operating schedule to align PV performance with AEM electrolyzer characteristics, where the AEM efficiency and flow rate has been taken into consideration. Finally, the performance of the open-source converter was compared with a lab bench power supply by monitoring the hydrogen production flow rate at a specific power level and the quality of the produced hydrogen. The results are presented and discussed in the context of both the potential for green hydrogen as well as accelerating PV deployment.

2. Methods

Currently developed PV-powered electrolyzer systems utilize both PV and grid power (Hassan et al., 2015; Rouholamini and Mohammadian, 2015) to operate at higher efficiency or are directly tied to PV as an only load (Atlam et al., 2011; Đukić and Firak, 2011; Maeda et al., 2012). The latter typically operate while the PV power is available, making them dependent on solar availability (Khalilnejad et al., 2016; Muhammad-Bashir et al., 2020; Rahim et al., 2015). This research addresses a different aspect by targeting the use of surplus energy produced by an installed PV system that exceeds the load. The aim is to operate the AEM to reduce or utilize this surplus energy for producing and storing hydrogen. To facilitate easy integration with any existing system, it is necessary to develop a DC-DC

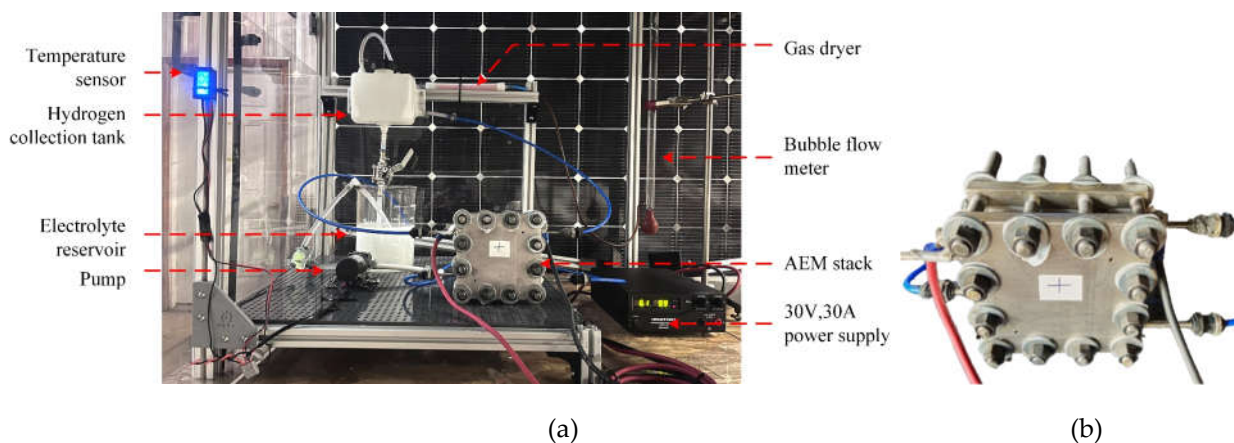
adjustable converter. This converter will enable the AEM to operate at its optimum efficiency without disrupting the continuous operation of existing loads. This approach ensures that the surplus energy is effectively utilized, enhancing the overall efficiency and sustainability of the PV system.

Although in the context of a conventional PV system, the AEM will function as a non-critical load and can be operated based on the availability of excess PV power, it is important to operate at the highest efficiency of the AEM. To achieve this, a small portion of existing battery capacity will be utilized for power leveling, allowing operation at a fixed current and voltage according to the AEM efficiency data. Thus, the system does not require any addition battery to optimize based on the load as might be done for a conventional PV battery system; the focus, instead, is on optimizing the AEM operation time and duration to maximize operational hours without depending on the battery. The battery is thus much smaller and less costly than a conventional PV battery system. To accomplish this a scheduling scheme is necessary for the AEM operation for maximizing the total yearly H_2 production by ensuring optimal AEM operation at fixed power while utilizing a small battery capacity. The operating time for all the days within a specific month was assumed to be the same, thereby minimizing the impact of the unpredictable nature of PV generation. A scheduling scheme is developed and simulated with Solar Alone Multi-objective Advisor (SAMA) open source software to provide an estimation of operating time and schedule (Ali Sadat et al., 2023; Sadat and Pearce, 2023). This approach will also provide a scheme for all other non-critical load operating times based on available PV power, allowing for the reduction of PV power wastage without the need to increase battery size and concomitant costs.

2.1. AEM Specification and Setup

The AEM electrolyzer (Cipher Neutron, Toronto, Canada) has an operating voltage ranging between 0V up to 6.6V. The electrolyzer has 3 cells and the plates area is 50 cm² with a current range up to 50A at 70°C. The electrolyzer cell and the setup of the experiment is shown in Figure 1. Tests were completed at room temperature (20°C) with a solution of 1 mole concentration of potassium hydroxide (KOH). The lower flow rate at minimum supplied power was measured with a manual bubble flowmeter (SUPELCO 2-0433, Pennsylvania, USA) and repeated three times for each reading. The instrument flow rate was measured at different current levels in intervals of 2A, from 2A to 16A using first an adjustable power supply by Circuit Test model PSC-6632 (Burnaby, Canada) (87% conversion efficiency) and comparing the results with the open-source adjustable DC-DC converter developed in this research work. Considering an additional power requirement of 35W for the pump and sensors, the total continuous power requirement of 100W is required for the AEM. To analyze the purity of H_2 produced by the AEM, hydrogen was collected and tested in the micro gas chromatograph (MicroGC) Varian CP-4900 (California, USA). The efficiency of the AEM is determined by equation 1.

$$\text{Efficiency (\%)} = \frac{\text{Higher Heating Value (HHV) of 1kg } H_2 \text{ (in kWhr)}}{\left(\frac{11126}{(\text{flowrate (lphr)})^2} \times \frac{3}{2}\right) (\text{in hr}) \times \text{Electrical power (kW)}} = \frac{39.4 \text{ (kWhr)}}{\text{Electrical power consumed for 1kg } H_2 \text{ production (kWhr)}} \quad (1)$$



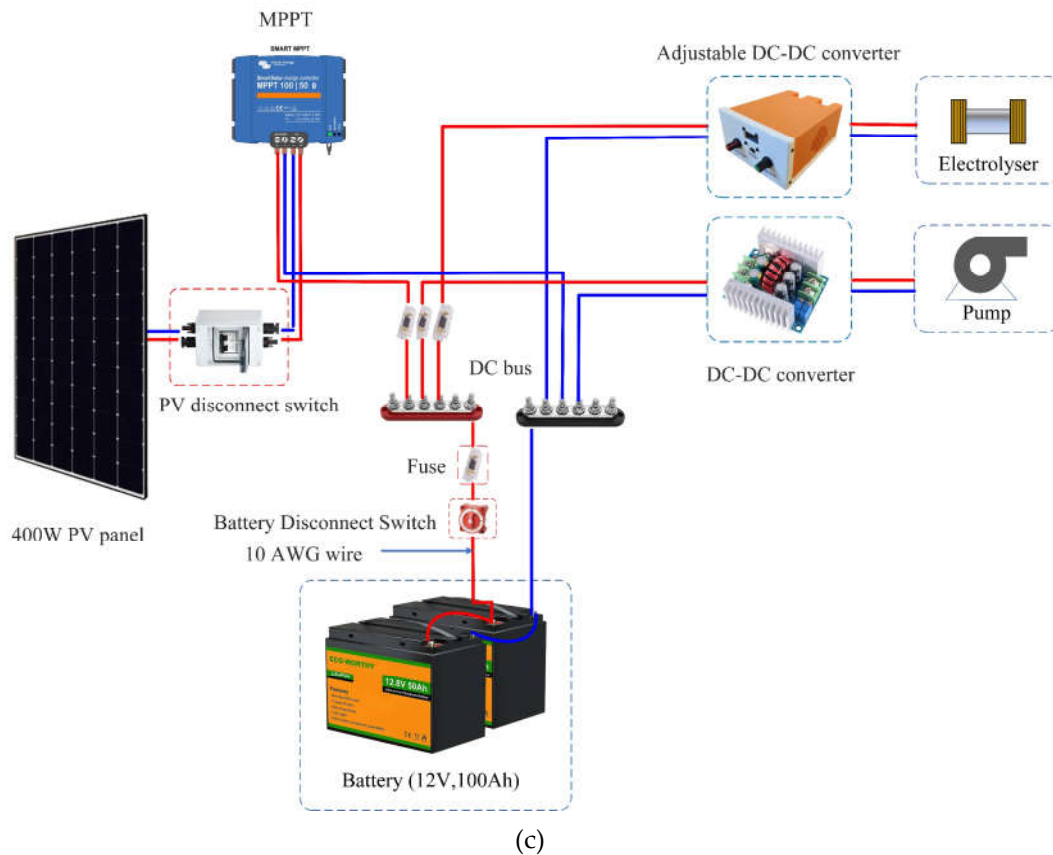


Figure 1. (a) Electrolyzer testing setup; (b) 3 cell version of Cipher Neutron AEM; (c) wiring diagram.

2.2. System Design

To simplify this research, PV-generated power data equivalent to a 400W PV module is considered as the system's excess power to representing an existing setup with surplus PV-generated data. To limit the dependency on the battery, only two 12V, 50Ah batteries are considered as part of the existing surplus system. The aim is to integrate the AEM with the 12V system for harnessing PV energy while taking full advantage of PV generated power. To operate the AEM at its optimal efficient current, an adjustable DC-DC converter with constant voltage and constant current capabilities ranging from 0-12V and 0-20A is designed and another 12V converter is used to supply power to the pump and temperature sensor, while the pump requires maximum of 4A at 12V. To integrate the PV system with the DC bus bar, a maximum power point tracker (MPPT) rated at 30A is employed.

2.3. AEM Scheduling

In a particular system with a defined surplus energy capacity, the objective is to optimize AEM scheduling only utilizing the excess energy without relying on the battery and primarily operating based on PV power generation.

Method 1: To utilize the excess energy without adding additional batteries into consideration and without disrupting the operation of the existing load, scheduling is possible only based on excess PV data. When the excess energy exceeds the optimal operating power of the electrolyzer, the AEM will turn on; otherwise, it will remain off. While this approach utilizes PV energy, the unpredictable nature of PV results in an unpredictable AEM schedule, necessitating automation of the system.

Method 2: To achieve more control over scheduling and ensure continuous, uninterrupted operation consistent throughout each day of the month, with only the pattern varying from month to month, the scheduling of the off grid electrolyzer can be done based on two factors: the optimal daily operating hours of the electrolyzer and the start and end times of its operation. These two factors can

be optimized to minimize PV power wastage and unmet load. This approach is the opposite of the PV and battery optimization technique. Here the plan is to schedule the load in such a way that PV wastage and unmet loads are minimized. In this context, unmet load refers to instances where, despite efforts to minimize PV wastage, the scheduled AEM operation may be interrupted as the AEM operation schedule for all the days of a month remains the same, while there are variations in solar irradiance patterns throughout the month. The following steps have been taken to determine the optimal scheduling of load.

Step 1. Collect monthly PV generation data at the optimal tilt angle of 34° to maximize annual energy production for case study location of London, Ontario, Canada.

Step 2. Process the PV data to calculate the average PV generation for each hour of a day, separately for each month. This 24-hour data is used to set the optimal AEM starting time based on average hourly PV power exceeding the electrolyzer power demand. This step also provides the minimum operating hours for each month, calculated from the number of consecutive hours when PV generation surpasses the electrolyzer operating power. The maximum operating hours are determined by dividing the total monthly excess PV power generation by electrolyzer power consumption.

Step 3. Estimate the daily operating hours between the minimum and maximum thresholds based on the AEM start time identified in the previous step for each month. Operating hours within this range need to be selected to explore various scenarios, using simulation results to confirm the optimal scheduling. Initially, the operating hours are to be selected lower than the maximum in order to minimize unmet load. Then the surplus electricity hours and unmet load needs to be monitored throughout this process while the next case is assumed based on the monthly surplus and unmet load data.

Step 4. After running several case-based studies, the best scenario is selected using predefined criteria, considering the impact of each case to minimize both excess electricity and unmet load. Both of these factors have different value ranges (Vafaei et al., 2020) and also there exists an inverse relationship between them. Thus, the impact normalizes the values of both excess energy and unmet load, taking them into account collectively as per equation (2), with the minimum value being considered optimal.

$$Impact = w_1 \times \frac{Excess\ electricity}{Maximum\ excess\ electricity\ in\ all\ cases} + w_2 \times \frac{Unmet\ load}{Maximum\ unmet\ load\ in\ all\ cases} \quad (2)$$

One important consideration is that in this analysis, both unmet load and excess energy wastage have been given the same weight ($w_1=1$ and $w_2=1$). If minimizing excess energy is prioritized over unmet load, the weights should be adjusted accordingly, which might result in a different optimal case, and vice versa. Lastly, the load is adjusted to eliminate the unmet load from the scheduled load data. The steps are highlighted over the flow chart in Figure 2.

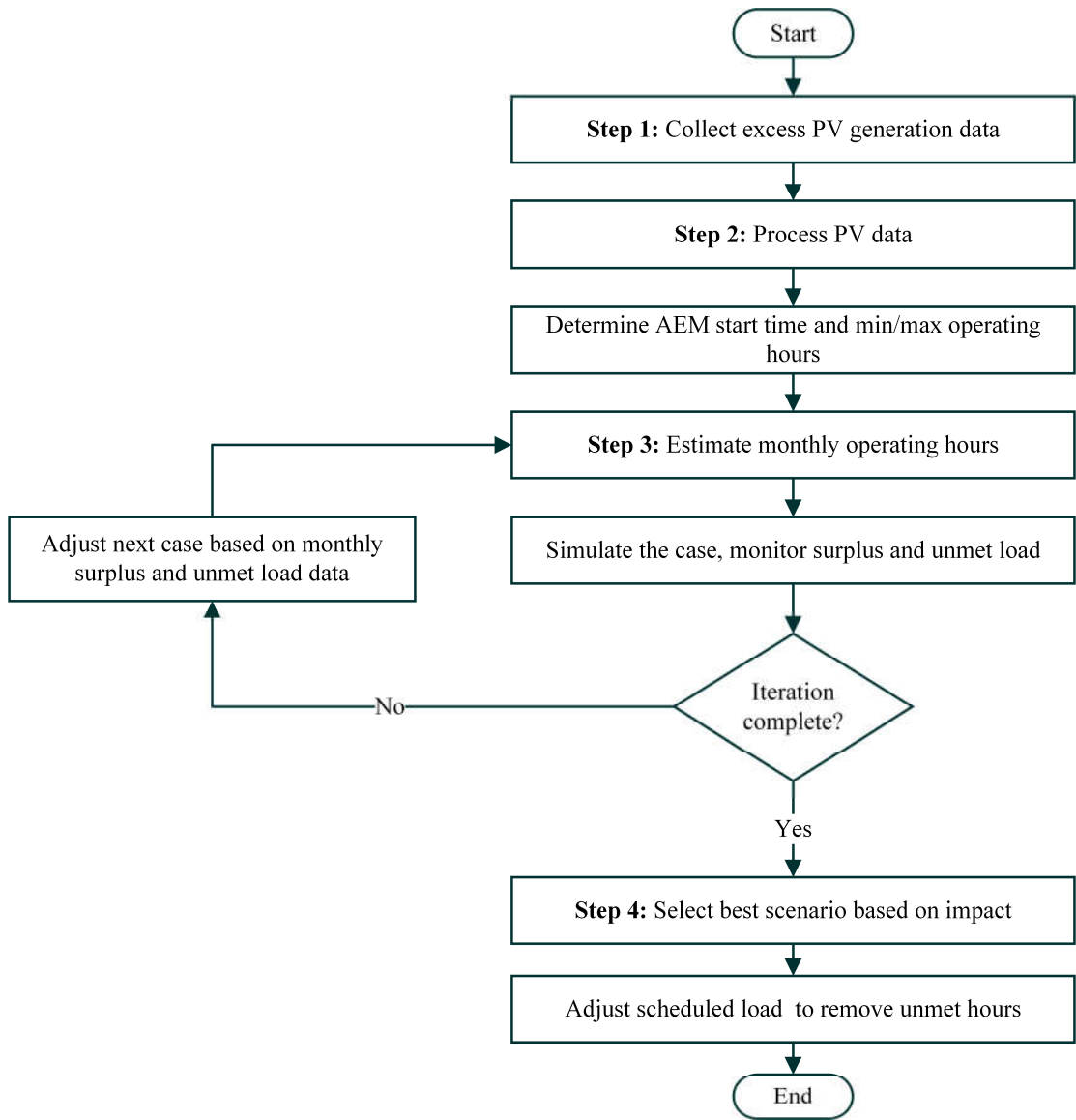


Figure 2. Flow chart of optimizing AEM operating schedule (Method 2).

2.4. Adjustable DC-DC Converter Design

To operate the electrolyzer efficiently at a pre-determined operating current (10-15A), an adjustable DC-DC converter was designed based on the open-source Arduino Nano (Arduino, Turin, Italy), which automatically selects constant current and constant voltage mode operation based on set voltage and current. These can be adjusted by two rotary potentiometers of 10kΩ connected to the analog pins of the Arduino. The converter used here is a synchronous buck converter where IRF3205 MOSFETs (75A) are used as switches. IR2104 MOSFET driver IC is used to provide complementary pulse width modulation (PWM) pulses to both low side and high side MOSFETs, the MOSFET driver circuit consists of a bootstrap capacitor of 10μF.

The capacitor and inductor size of the buck converter is selected above their critical value to keep the voltage ripple (ΔV_o) within 1% while maximum 25% current ripple (Δi_L) at the maximum inductor current rating with 25kHz switching frequency (f_s) of the MOSFETs. The adjustable DC-DC buck converter is meant to be connected to a source voltage (V_s) of 12V and supplying AEM around 6V at output (V_o), so the converter is designed considering this scenario as optimal. This gives an optimal duty cycle (D) 50% for the converter design. Also, the maximum power rating is considered 120W, 20A for 6V, which requires designing the converter with 20A average inductor current. The

critical inductor (L_{crit}) and capacitors (C_{crit}) values are calculated based on the following equations (3) and (4) and the variables are defined along with their values in Table 1.

$$L_{crit} = \frac{(V_s - V_o)D}{f_s \Delta i_L} \tag{3}$$

$$C_{crit} = \frac{(1 - D)}{8 \left(\frac{\Delta V_o}{V_o} \right) L_{crit} f_s^2} \tag{4}$$

Table 1. Parameters of adjustable DC-DC buck converters.

Parameter	Value
Max load power	120 W
Input voltage V_s	12V
Output voltage V_o	6V
Duty cycle (d)	50 %
Average current (I_{avg})	20 A
Ripple Current (ΔI)	5 A
Peak inductor current (i_{peak})	25 A
Critical Inductance (L_{crit})	24 μ H
Critical output capacitor (C_{crit})	416.67 μ F
Inductance (L)	25 μ H, 25A
Output capacitor (C_o)	470 μ F, 25V
Input capacitor (C_{in})	470 μ F, 25V

The inductor and capacitors of the buck converter are selected above their critical value and the schematic of the converter is shown in Figure 3.

For designing the inductor, toroidal inductor core 0078934A7 from Magnetics (Butler, Pennsylvania, USA) is used which is 26.92mm in outer diameter and 11.18mm in height, has relative magnetic permeability 90 and inductance factor 113nH per turn. The design parameters for the 25 μ F, 25A inductor are shown in Table 2.

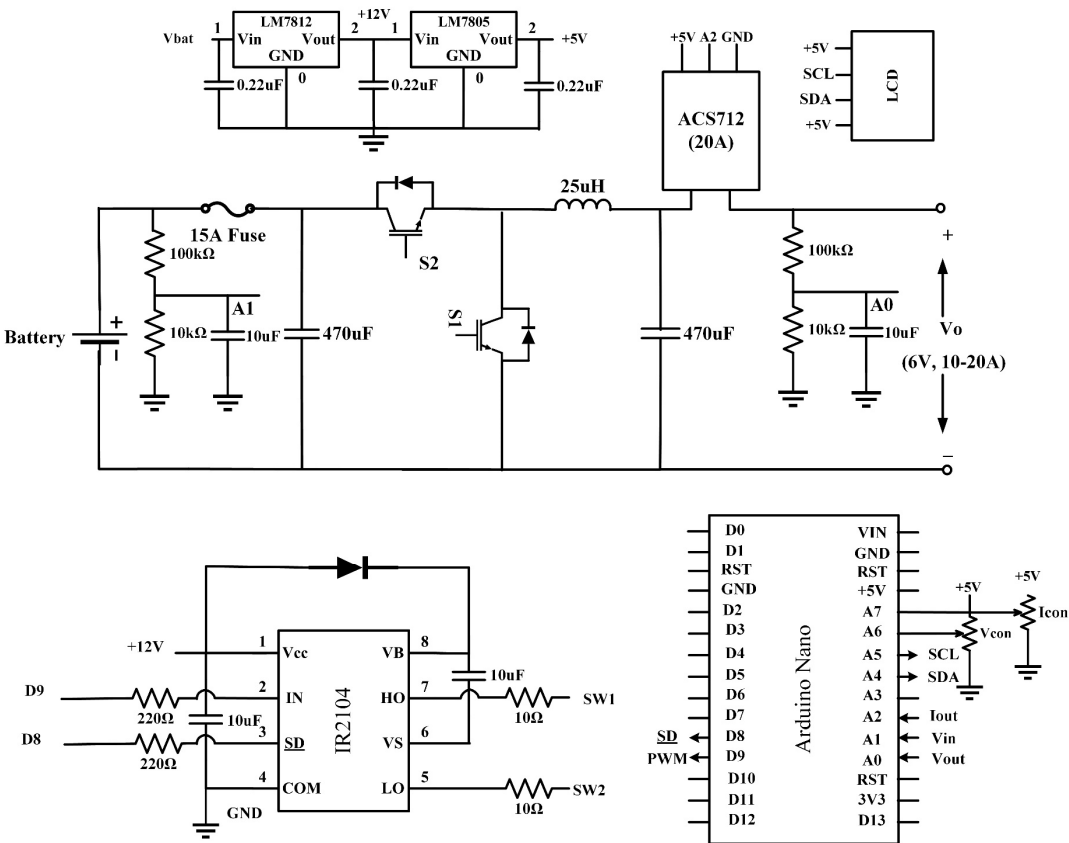


Figure 3. Schematic of adjustable DC-DC synchronous buck converter.

Table 2. Inductor design parameters (Magnetics, 2024).

Parameters	Values
Number of Turns	22
Wire Size (AWG)	16 AWG
Winding Factor	20.8%
DC Resistance	12.49 mΩ
Finished OD	30.7 mm
Finished HT	15 mm
Total Wire Length	947 mm
Saturation current I_{sat}	38.9107 A

All the converter related files, Arduino code and 3-D printed parts design files along with the bill of materials and the 3-D printing parameters are available under open source licenses (Rahman et al., 2024). The 3-D printed enclosure (Figure 4(a-c)) is designed in two parts in FreeCAD (Version: 0.21.1) and printed in a RepRap class (Sells et al., 2009; Jones et al., 2011; Bowyer, 2014) open source Prusa Mk3 (Prusa Research, Prague, Czech Republic) printer using poly lactic acid filament with 0.6 nozzle (layer height 0.3 and infill 20%) and later assembled with its snap fit mechanism along with M3 screws to secure the assembly.

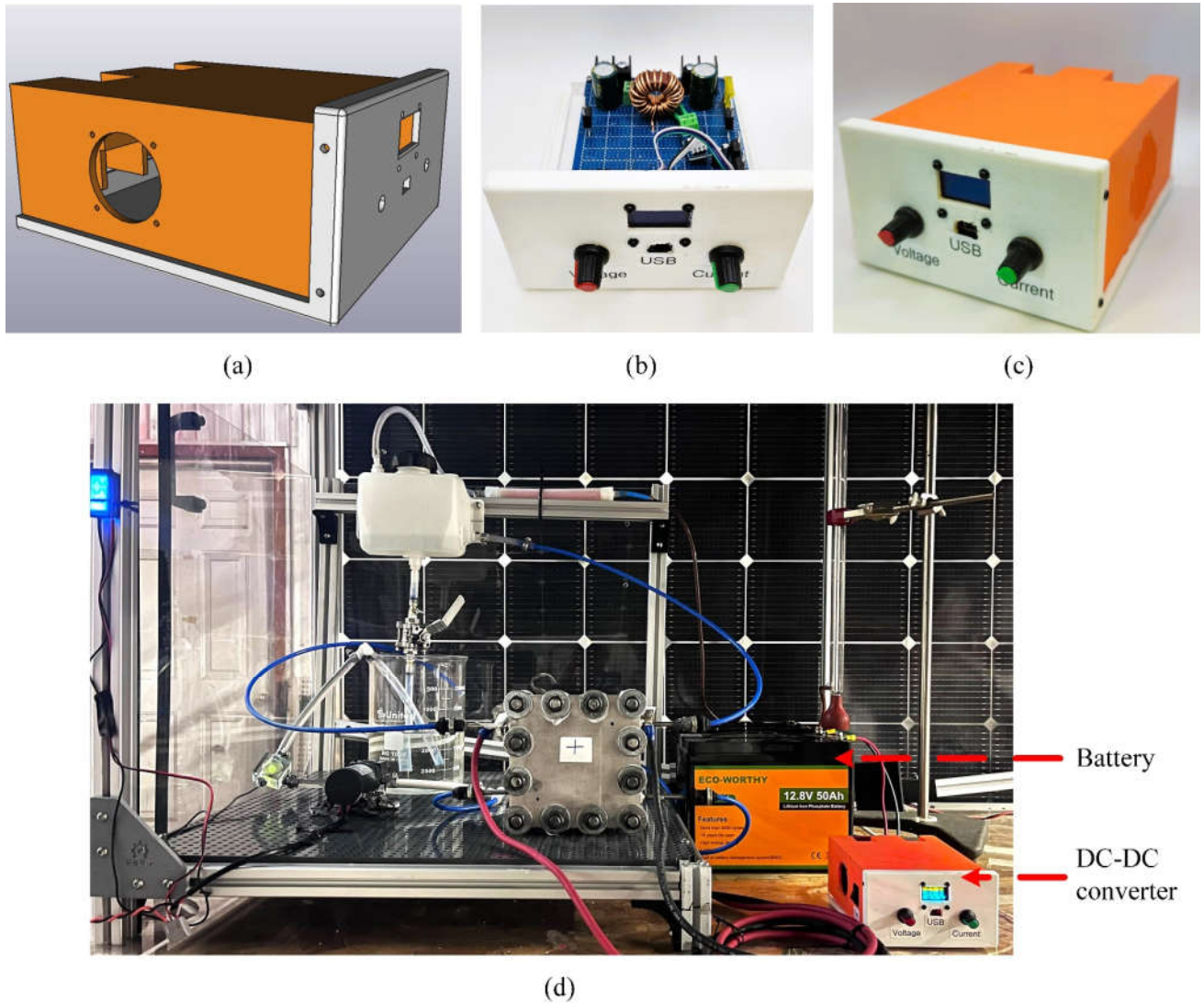


Figure 4. (a) 3-D enclosure design; (b) PCB design of DC-DC converter; (c) Assembly of the converter; (d) Final off grid PV supply setup for AEM electrolyzer.

3. Results

3.1. AEM Scheduling

Following the method described above the optimal operation schedule for the AEM system was developed. Initially, hourly PV generation data for a 400W PV module was determined using SAMA, as depicted in Figure 5. In method 1, scheduling of the electrolyzer was done based on the hourly excess PV data, only scheduling the AEM when the excess PV power surpassed the operating power threshold (100W).

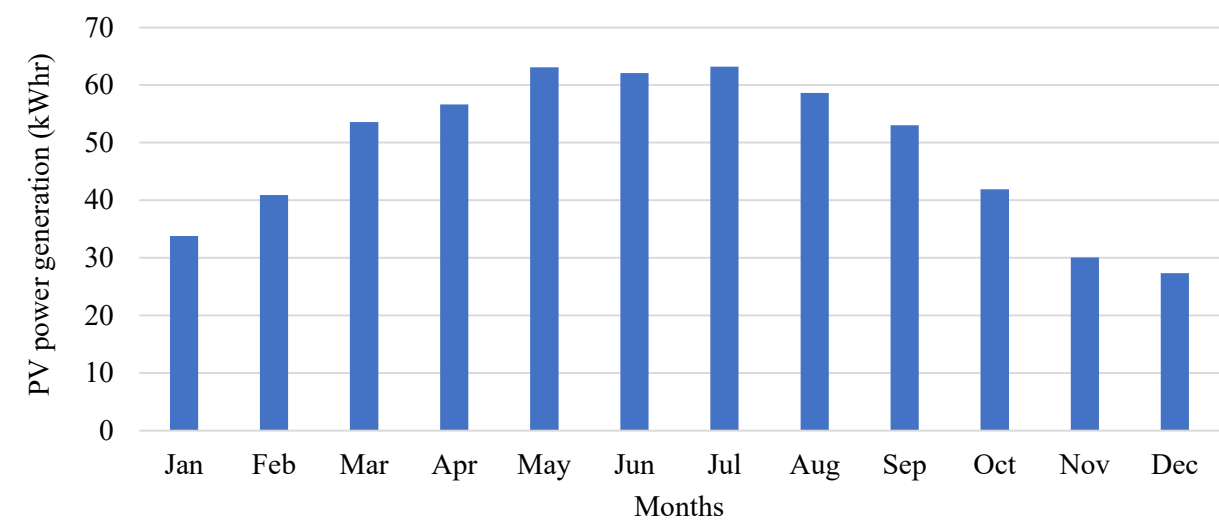


Figure 5. Monthly PV power generation for 400W PV module at 34° tilt angles in London, ON.

In method 2, based on average 24-hour PV power generation data, the optimal start times for each month, along with the minimum and maximum operating hours, were identified and shown in Table 3.

Table 3. Hourly average PV power generation to find operational hours (marked in green) for each month.

Mont	6AM	7A	8A	9A	10A	11A	12P	1P	2P	3P	4P	5P	6P	Min	Max
h	M	M	M	M	M	M	M	M	M	M	M	M	M		
Jan	0.00	0.00	0.05	0.09	0.15	0.16	0.18	0.16	0.14	0.09	0.07	0.00	0.00	5	10
Feb	0.00	0.02	0.07	0.12	0.17	0.21	0.22	0.19	0.19	0.14	0.09	0.04	0.00	7	14
Mar	0.00	0.05	0.11	0.18	0.21	0.22	0.23	0.24	0.20	0.15	0.10	0.05	0.00	8	17
Apr	0.02	0.07	0.13	0.17	0.23	0.23	0.25	0.24	0.20	0.16	0.11	0.06	0.01	9	18
May	0.03	0.10	0.14	0.19	0.22	0.24	0.25	0.23	0.22	0.19	0.12	0.07	0.02	9	20
Jun	0.04	0.09	0.14	0.19	0.23	0.25	0.26	0.24	0.21	0.18	0.13	0.08	0.03	9	20
Jul	0.03	0.08	0.14	0.18	0.22	0.24	0.26	0.24	0.22	0.17	0.12	0.08	0.03	9	20
Aug	0.02	0.07	0.12	0.17	0.20	0.22	0.25	0.24	0.21	0.17	0.12	0.07	0.02	9	18
Sep	0.01	0.06	0.13	0.17	0.21	0.23	0.24	0.22	0.19	0.15	0.10	0.05	0.00	9	17
Oct	0.00	0.05	0.09	0.16	0.16	0.18	0.19	0.18	0.14	0.12	0.07	0.02	0.00	7	13
Nov	0.00	0.01	0.07	0.11	0.13	0.14	0.14	0.13	0.13	0.09	0.04	0.00	0.00	6	10
Dec	0.00	0.00	0.05	0.09	0.12	0.14	0.14	0.12	0.11	0.08	0.04	0.00	0.00	5	8

Various scenarios were considered and simulated in SAMA using the load following dispatch technique to determine the optimal monthly operating hours. This involved varying the operating hours each month while monitoring surplus electricity hours and unmet load. Ten different cases were evaluated. Each case in Table 4 was selected based on the unmet and excess load data from the previous scenario, allowing for iterative optimization.

Table 4. Cases considered based on different monthly operating hours for optimal scheduling.

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Case 1	8	12	15	15	16	16	16	14	14	10	8	6
Case 2	7	11	12	13	15	15	15	13	12	8	7	5
Case 3	7	10	11	12	14	14	14	12	11	7	6	5
Case 4	7	10	11	13	15	15	15	13	12	7	6	5
Case 5	8	12	15	16	18	18	18	16	15	11	8	6
Case 6	7	10	12	13	15	15	15	15	13	9	6	5
Case 7	7	10	11	14	16	16	16	14	12	9	6	5
Case 8	7	9	11	14	16	16	16	14	11	9	6	5
Case 9	7	8	11	14	15	16	16	14	12	9	7	5
Case 10	7	9	12	14	16	17	17	14	12	9	6	6

Based on the analysis of excess energy wastage and unmet load data across these cases, it was determined that Case 8, as presented in Table 5, provided the optimal scheduling solution. This case successfully minimized both excess energy and unmet load as the value of impact (equation 2) is minimum in this case (Figure 6), ensuring efficient and effective operation of the AEM system. From Table 5, it is evident that the optimal case should be around a scheduled load of 408 kWhr. Any increase or decrease from this point would raise the impact.

Table 5. Excess electricity, unmet load, and impact for cases.

Case	Total PV power [kWhr]	Scheduled load [kWhr]	Excess electricity [kWhr]	Unmet load [kWhr]	Impact
Case 1	584	456.1	146	41.8	1.44
Case 2	584	404.3	185	23.5	1.29
Case 3	584	374.0	211	15.4	1.27
Case 4	584	392.3	194	19.5	1.27
Case 5	584	489.8	122	56.2	1.58
Case 6	584	410.8	178	24.5	1.28
Case 7	584	413.8	174	24.6	1.26
Case 8	584	408.0	179	22.6	1.25
Case 9	584	408.1	180	23.7	1.27
Case 10	584	423.3	167	27.8	1.29

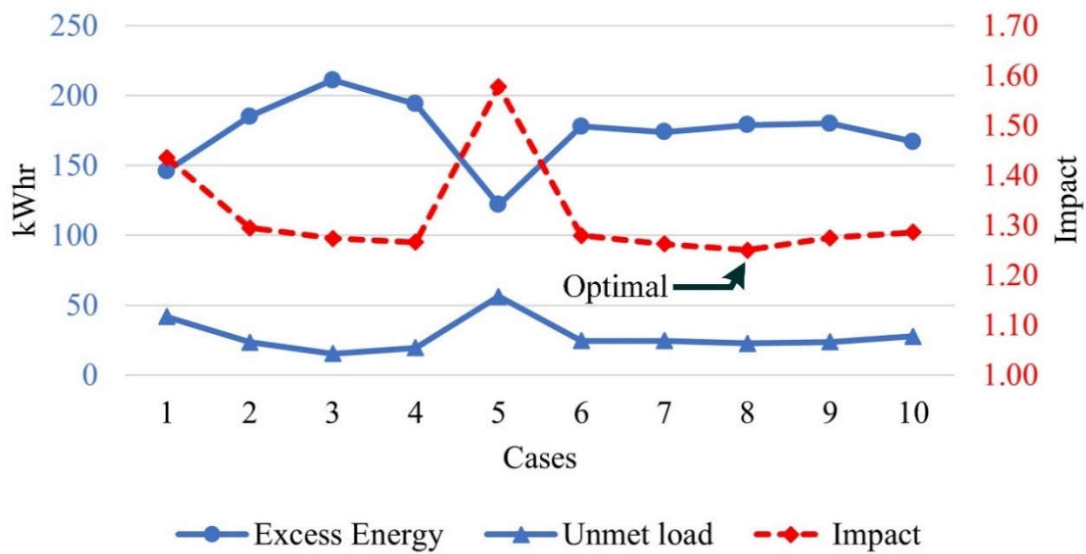
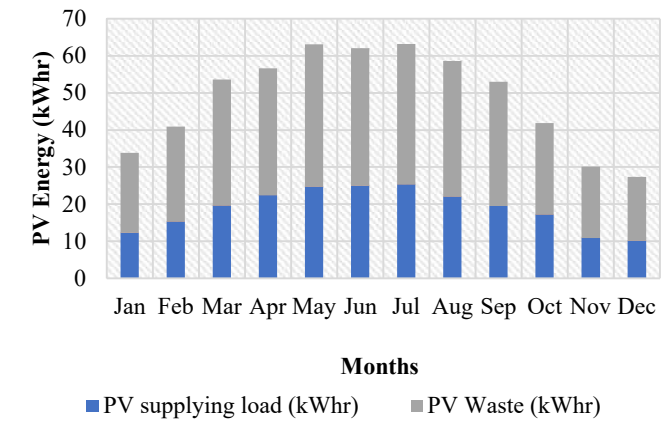


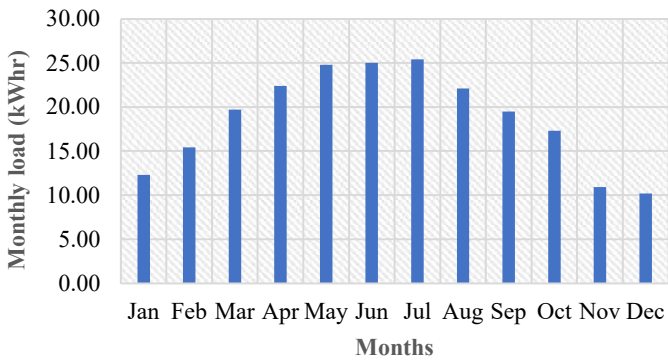
Figure 6. Case based excess energy and unmet energy plot. The optimal impact is highlighted.

3.2. Off Grid PV System’s Performance and Energy Usage

In method 1, the PV system with a capacity of 400W was analyzed, generating an annual PV power output of 584.05 kWh. Although the system successfully met the annual load requirement of 225 kW (Figure 7) ensuring a fully served load with no capacity shortages, the scheduled load was unable to utilize 359.04 kWh of the initial total excess energy. Thus, a significant 61.5% of the total power remains unused, leading to substantial energy waste.



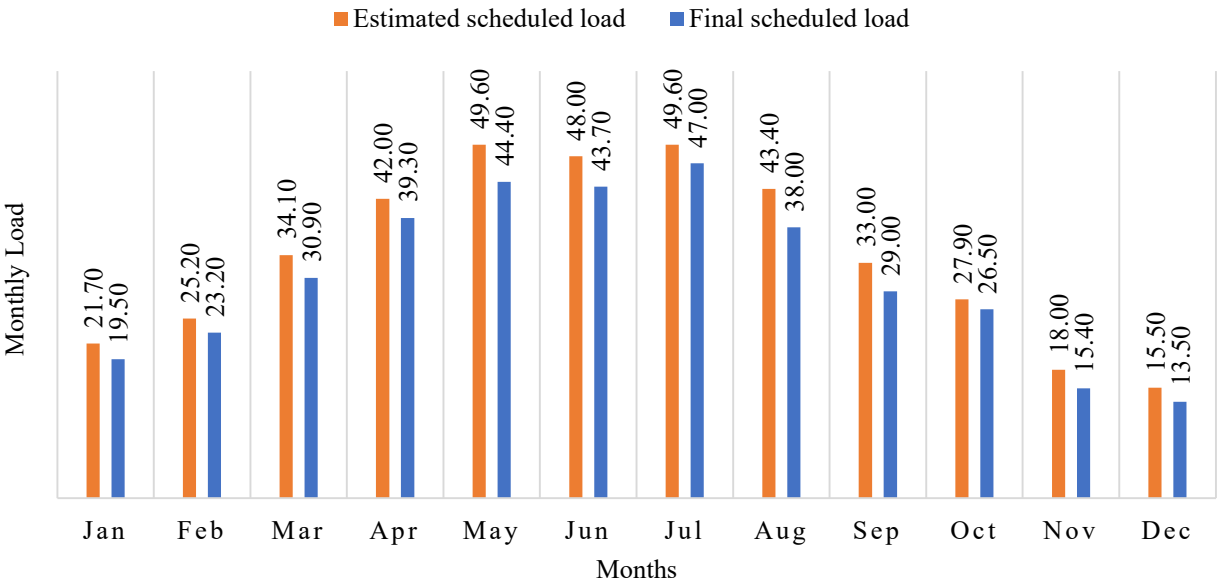
(a)



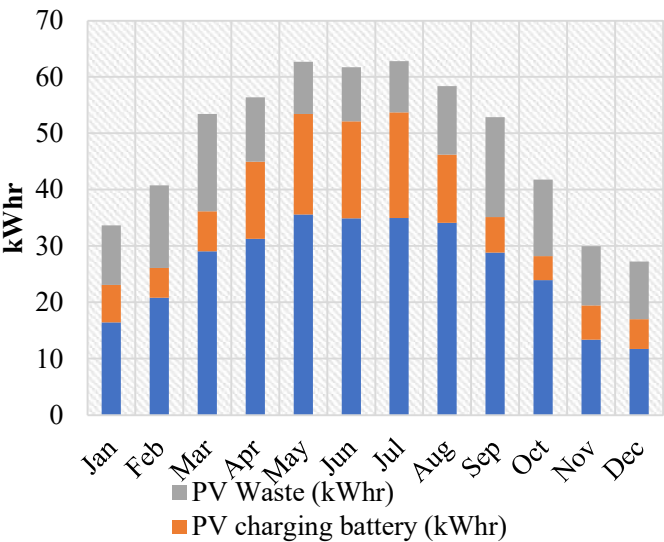
(b)

Figure 7. (a) Utilization of PV energy by AEM, battery charging and wastage. (b) Monthly scheduled load based on method 1.

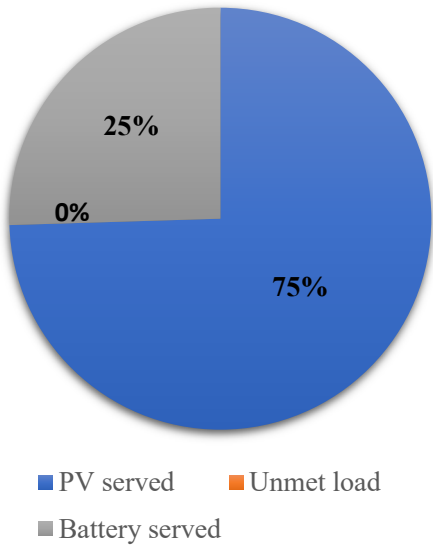
For method 2, in the best-case scenario (Case 8), the annual load estimation is 408 kWh (Figure 8(a)), has an unmet load of 22.6 kWh. After removing the unmet portion from the estimated schedule, a final schedule (370.4 kWh) is prepared, and this revised load scenario is then re-simulated in SAMA. Additionally, Figure 8(b) illustrates the utilization of PV energy, offering insight into how PV power drives the AEM and stores excess energy in the battery along with the energy waste. Furthermore, Figure 8(c) confirms that the scheduling scheme enables the AEM to operate on PV power for 75% of the total scheduled operation, with only 25% provided by the battery, and 0% of unmet load.



(a)



(b)



(c)

Figure 8. (a) Monthly scheduled load based on case 8; (b) Utilization of PV energy by AEM, battery charging and wastage; (c) Sources of scheduled AEM power.

3.3. AEM Characteristics

The electrical characteristics of AEM while the electrolyzer was working at 20°-30°C, shown in Figure 9(a). In Figure 9(b) the results obtained in terms of gas production measured through the flowmeter is displayed.

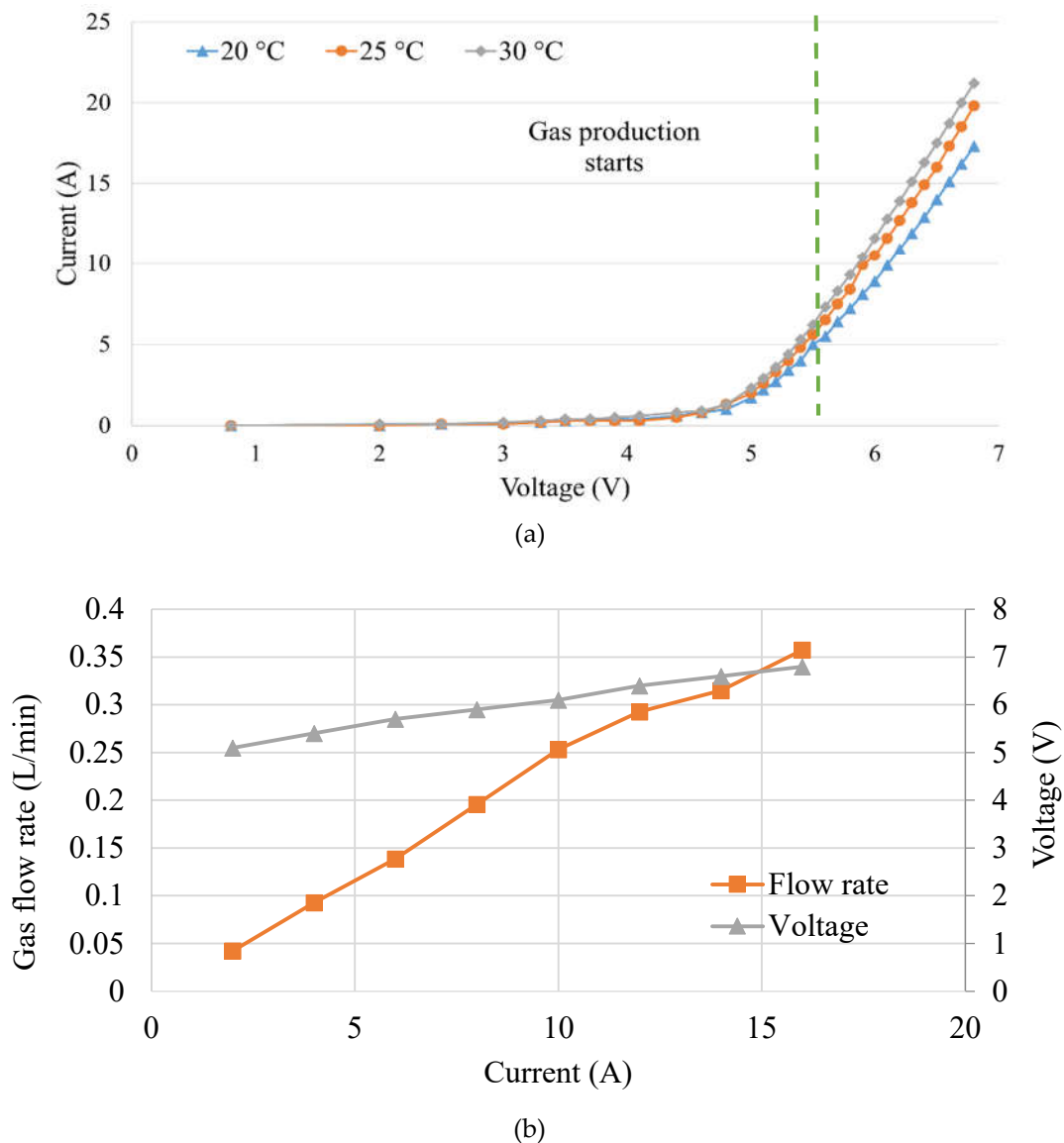


Figure 9. (a) Current vs voltage characteristics curve of AEM electrolyzer; (b) Gas flow measurements.

Consequently, the efficiency of the electrolyzer has been determined using Equation 1. Figure 10(b) shows how the AEM efficiency remains approximately at 60% until the current reaches 10A (65W), after which it begins to decline slightly around 50%, which leads to selection of 10A as the optimal operating current for the subsequent experiments. Analyzing the hydrogen produced in this process is tested in the MicroGC, and it has been demonstrated the purity of the produced H₂ is 96.1% as shown in Figure 10(a) through the chromatogram.

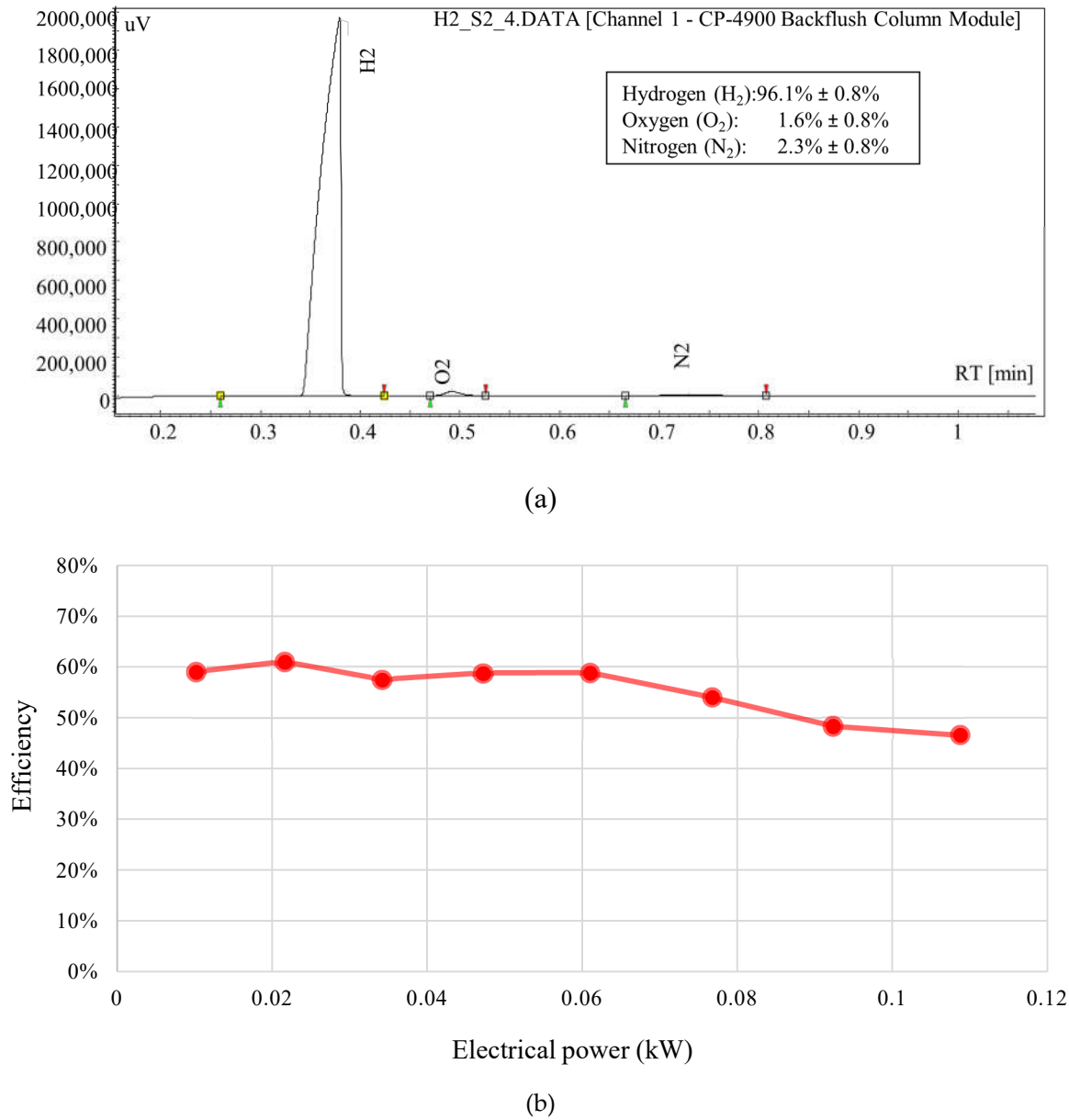
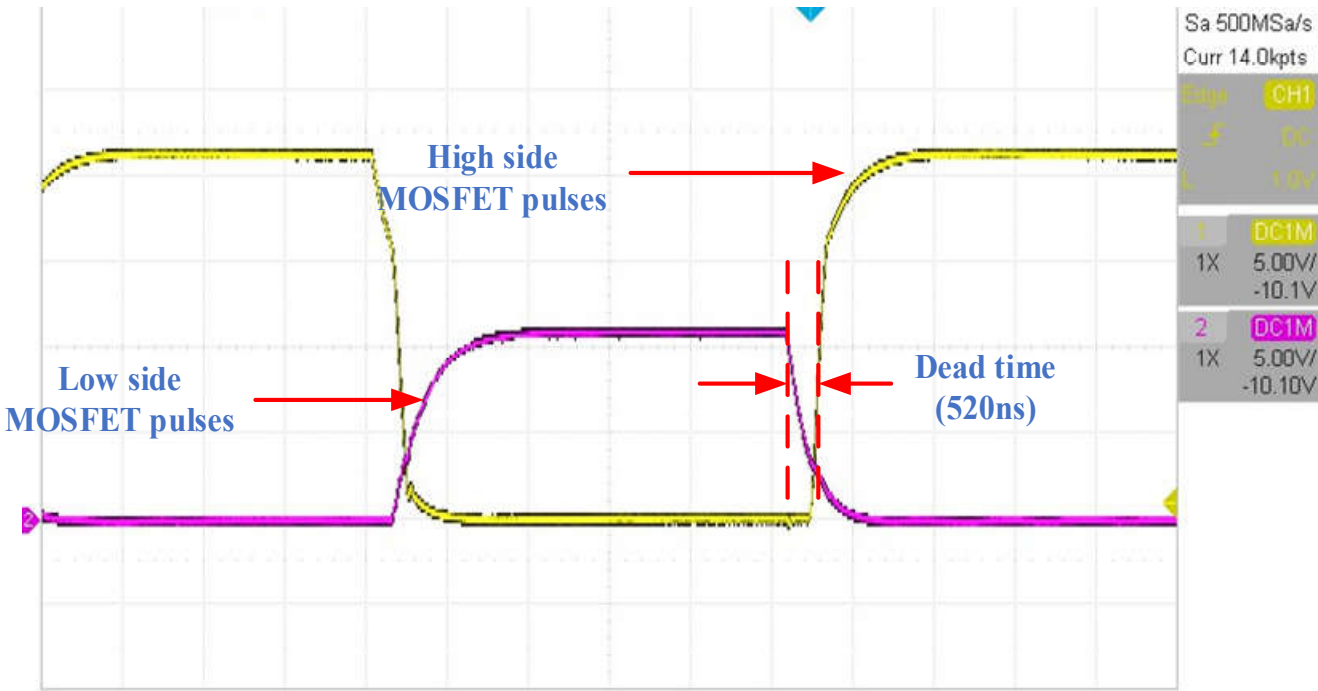


Figure 10. (a) MicroGC chromatogram; (b) Efficiency vs power consumption of AEM.

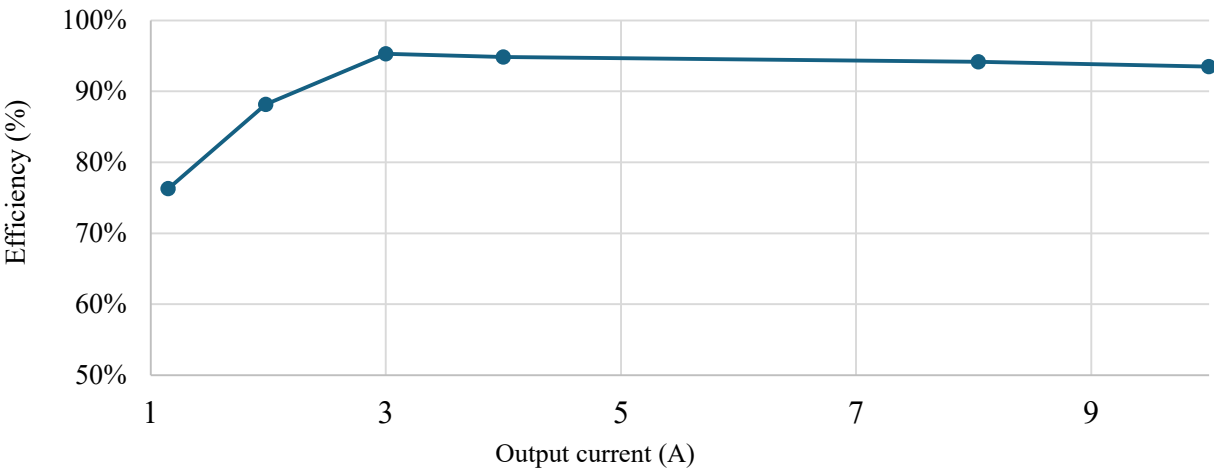
3.4. DC-DC Converter Performance

3.4.1. Output Voltage Quality and Efficiency Measurement

A synchronous buck converter topology has been adopted in this research to achieve better efficiency than the conventional buck converter. In addition, the complementary MOSFET switching pulses have dead time of 5.20×10^{-7} s to reduce switching losses by implementing ZVS (Figure 11(a)). Along with this using a larger output capacitor and higher switching ensures better quality of output voltage. For a wider range of load current the efficiency varies slightly, but remains above 90% as seen in Figure 11(b).



(a)



(b)

Figure 11. (a) Complementary pulses and dead time; (b) Efficiency as a function of output current.

3.4.2. A Comparative Study of Grid-Connected Power Supply vs. Open-Source Converter with Solar Power

From the AEM efficiency versus electrical power plot in Figure 10(b), efficiency is found to be approximately 60% for operating current ranging from 8A-14A. For this study 10A is considered as optimum operating current and the AEM is operated at this current for 60 minutes for both the grid connected and off-grid PV setup at the same 10A current. The two setups are directly compared based on measuring the flow rate in each in three minutes interval. From Figure 12 it is clear that for both setups, the flow rate almost remains stable for 10A, although a little fluctuation may be caused by experimental measurements using a manual bubble flowmeter (3.5% variance) as shown by the variance values in Figure 12. Throughout the period of experiment for the setup the flow rate of hydrogen is found to be around 0.25 L/min.

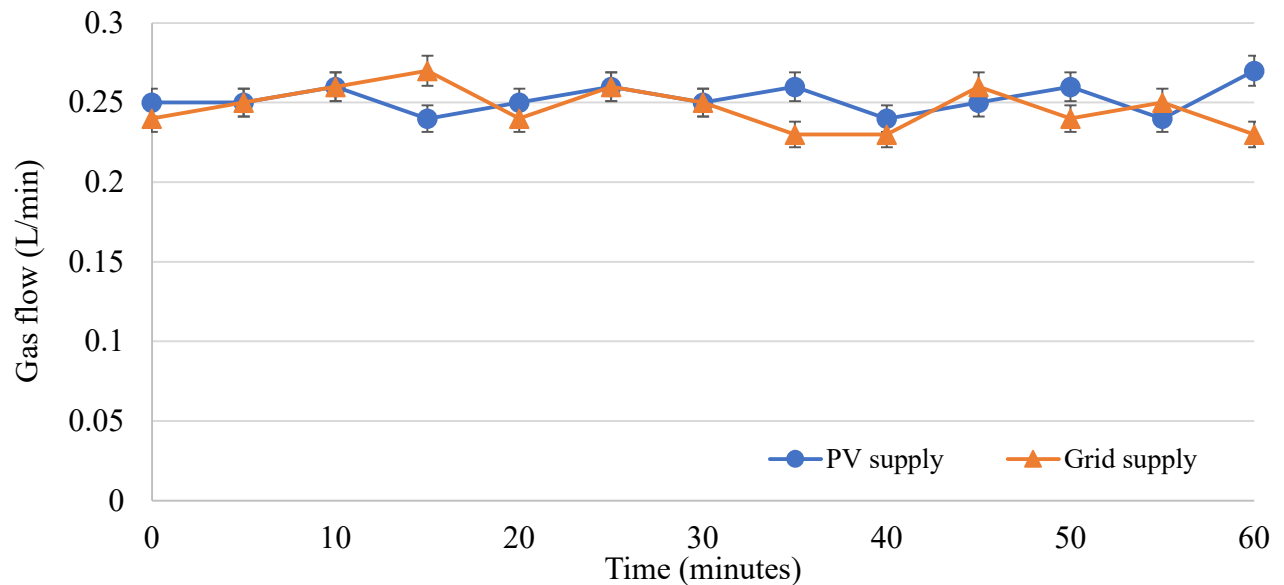


Figure 12. Flow rate vs time (grid vs off grid).

4. Discussion

Green hydrogen production utilizing renewable energy provided through grid power is increasingly becoming mainstream (Bianco and Blanco, 2020; Islam et al., 2024; Li et al., 2022), although the potential for incorporating solar DC power directly into the process is foreseeable. Additionally, the requirement of DC power for electrolysis adds further potential efficiency gains. There have been very few instances where DC power is directly employed (Gibson and Kelly, 2010, 2008), and utilizing excess energy of an already existing PV system makes the approach used here unique. PV systems have become the lowest-cost form of electricity generation in many areas, offering a sustainable alternative to fossil fuels (Bellini, 2021; Kennedy, 2023). The intermittent nature of solar energy can present a challenge for grid operators (Anees, 2012; Pérez-Arriaga and Batlle, 2012). For example, the daily solar cycle can lead to an excess supply during peak sunlight hours, contributing to what is known as the "duck curve" (Jones-Albertus, 2017). To address this challenge, H₂ can be used as a form of energy storage by utilizing excess electricity generated from PV systems to electrolyze water into hydrogen. This stored energy can be used during periods of low solar output or high demand (IRENA, 2020b). This study provides an alternative, open-source solution utilizing direct PV power for the AEM electrolyzer. This open-source solution could significantly impact the hydrogen production industry as open source technologies can be scaled by any company (Chengalur-Smith et al., 2010; Pearce, 2015).

The results shown here not only demonstrate the feasibility, but also provide test results that validate the effectiveness of AEM electrolyzer when powered directly by solar energy in this configuration. The proposed method shows how utilizing the excess PV generated power, the opensource dc-to-dc converter as illustrated in Figure 11, maintains a steady-state operation for the electrolyzer. This setup, in those conditions consistently achieves an average flow rate of 0.25 L/min. Based on the planned operational hours, this results in an annual production of 57,810 liters of hydrogen, considering 15 L/hr over 0.1 kWhr of energy consumption and the 370.4 kWhr scheduled over the entire year using a single PV module. All aspects of this design can be increased to reach scale.

This study had several limitations that can be overcome in future work. Although, the number of cases considered for AEM scheduling here is adequate to get reasonable results; a higher number of cases might result in more accurate optimization. On the other hand, daily scheduling without the use of additional batteries, as mentioned in method 1, allows for very easy implementation of this system, but utilizes only less than half of the total excess power. Also predicting on PV power generation data in advance for proper scheduling, however, is still challenging as it depends directly

on weather prediction (Slingo and Palmer, 2011). In contrast, monthly scheduling combined with some battery storage will significantly reduce PV energy waste and unmet load issues. Heuristic search space methods, however, such as particle swarm optimization (PSO), can also be implemented in the future to find the optimal operating schedule (Oberloier et al., 2022). This requires incorporating a PSO into the SAMA code to identify the optimal scheduling. The PSO algorithm will vary the operating hours each month, creating new yearly load data. Based on this load data, SAMA will provide the yearly excess energy data and unmet load data and the optimal scheduling will be selected. In addition to optimal scheduling, integrating the scheduling scheme with the preexisting system and its existing load is essential for the feasibility analysis of the method. Finally, a life cycle assessment of the system may provide greater insight into its economic and environmental benefits of this approach for supporting distributed generation of PV (Roy and Pearce, 2024).

5. Conclusions

This study introduces a new approach for green hydrogen production, demonstrating the practical integration of an open-source DC-DC converter with solar photovoltaics to power an anion exchange membrane electrolyzer. The open-source converter, able to keep efficiency over 90%, has shown how it can be used to directly power the electrolyzer while taking advantage of solar energy surplus after all other electrical loads are met. This approach not only facilitates hydrogen production but also paves the way for further research in adjustable DC-DC converter topologies and their integration into hydrogen production systems. By strategically scheduling the demonstration AEM electrolyzer stack for maximizing the output hydrogen production and minimizing solar energy waste, the results show how even a small AEM of only 3 cells and 50cm² active area can effectively generate over 5 kg (57,810 L) of hydrogen per year. This hydrogen allows the excess solar electricity to be stored and utilized more flexibly. The scheduling scheme for non-critical loads based on the excess PV power of an existing system introduces innovative techniques to optimize load management. This approach enhances the utilization of off-grid PV power, shifting the focus from designing systems tailored to the load to optimizing the load for existing systems. This introduces a novel concept for off-grid PV system design, advancing the goal of adopting fully off-grid system by maximizing the full utilization of PV power capacity without relying on grid connectivity. By employing this sustainable method, the study highlights a scalable solution that not only enhances the efficiency of hydrogen production, but also promotes the deployment of renewable energy technologies. This exemplifies a significant advancement in the field of green energy, offering a potential pathway towards achieving carbon neutrality.

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