Solar Regenerative Hydrogen Fuel Cell Charging System

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Uriel Ruiz,

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Abstract- Due to increasing levels of air pollution from the use of fossil fuels, producing clean renewable energy has become a high priority in society. However, renewable energy like solar or wind energy can only be produced intermittently, and frequently does not align with the energy demand. This has become a significant barrier to the adoption of renewable energy. As a result, additional effort is required to harvest and store excess energy produced during peak production periods to meet the energy demand during off production periods. The objective of this study is to design a solar powered regenerative hydrogen fuel cell charging system that can store excess energy in the form of hydrogen and generate electricity using fuel cell when renewable energy is not available. A group of undergraduate engineering students at the University of California, Merced, designed, integrated, and tested the newly developed renewable energy charging system. This system is comprised of 6 photovoltaic modules rated at 3.0 W each, in-house designed gravity-assisted gas storage tanks, a 1.0 W water electrolyzer, and a 3.0 W fuel cell stack. The integrated system can produce up to 2.5 W to charge a cell phone day or night. During insolation, energy from the photovoltaic modules is used to directly charge the phone and power the water electrolyser for hydrogen generation. The 1.0 W water electrolyzer or electrolysis cell can produce more than 4.0 L of hydrogen under ambient pressure on an average day in Merced, CA. The generated hydrogen fills the storage system during insolation and is released to the 3.0 W fuel cell stack to charge various cell phones at night or during a cloudy day. A DC voltage booster was used to meet the charging requirement for voltage input (4.5 V-5.0 V). In this study, students successfully demonstrated that both solar and hydrogen energy can be used to meet the energy demand for charging a cell phone all year round. This system provides a proof-of-concept study to meet future energy demand with a sustainable solution. Further, various learning outcomes including problem solving, critical thinking, communication, and team work were fulfilled by this in-depth engineering project.

Index Terms- Fuel Cell; Water Electrolyzer; Solar Cell; Hydrogen; Hybrid; Clean Energy; Energy Storage; Regenerative System; Renewables; Demonstration; Education

I. Introduction

As human population, new technologies, and infrastructures continue to grow, there is a proportional increase in the demand for energy need. Currently, most energy in the United States is produced by fossil fuels. For the last century, petroleum, natural gas, and coal had accounted for at least 80% of the total U.S. energy consumption.[1]

However, burning fossil fuels produces pollutants and heat-trapping gases that increase global atmospheric temperatures. Global carbon emissions in 2013 were estimated at 9776 million metric tons, which represents a 1.1% increase over global carbon emissions in 2012.[2] Continued use of fossil fuels increases global pollutants and poses environmental threats.

Renewable energy sources such as wind and solar energy are potential alternatives to fossil fuels in which many businesses and governments have already invested. California's goal is to meet half of the state's energy demands with renewables by 2030, which is achievable through California's abundant access to solar and wind energy.[3] However, one of the primary drawbacks to solar and wind energy is that power production can fluctuate depending on weather conditions. To have a reliable energy source and prevent system failures, energy production must match or exceed energy demand. Due to these limitations, energy storage system, like mechanical, chemical, or electrical device, is required. Examples include utilizing pumped water or mechanical flywheels to store mechanical energy, or using banks of batteries and capacitors to store chemical energy.[4] Another method of storage is to store the energy as fuel, like hydrogen, which has higher energy density than batteries. This can be achieved by electrolysis using the excess energy produced by photovoltaics (PV) or wind to split water into hydrogen and oxygen via an electrolyzer.[5] The produced hydrogen is then stored to be used at a later time when solar or wind is unavailable. A fuel cell is a power conversion device that converts hydrogen directly to electricity at high efficiency. The operating principle is to combine hydrogen and oxygen in an electrochemical reaction, which creates electricity, water, and waste heat.[6] The whole system produces zero emissions and therefore is considered a renewable energy solution.

Many researchers have studied systems that integrate wind and photovoltaic power with fuel cells for a variety of applications and configurations. Most research had model simulations for power generation greater than 100W. In a study by Wang and Nehir, they simulated the sizing and power management of an 18 kW fuel cell hybrid system to provide power to five American homes in the Pacific Northwest.[7] Hosseini et al. also modeled a solar-fuel cell energy system to power a small apartment complex, using a Solid Oxide Fuel Cell (SOFC). Their SOFC met the power demand of the apartments, which is roughly 2.5kW during solar unavailability, contributing to a maximum total energy efficiency of 55.7%.[8] In place of a SOFC, Lehman created a solar-fuel cell hybrid system that implemented a Proton Exchange Membrane Fuel Cell (PEMFC) at a rating of 1.5kW.[9] Shapiro et al. described a 1 kW system with reversible fuel cell, similar to that described by Lehman, but sought to reduce parasitic loads.[10] The work of Bensmail simulated a 500W stand-alone system which provided an expected 24-hour power profile showing points of power supply transition in the hybrid system.[11] This system used both wind and solar energy to meet power demand, and used excess energy to generate and store hydrogen for later use in a fuel cell. The overall hybrid energy system has been studied in these examples, but were designed for a high power rating, and very little optimization was studied.

In our study, students designed the whole system from scratch by integrating PV, water electrolyzer, hydrogen storage, fuel cell, and power electronic components. At the completion, they have turned this educational and innovative engineering project into a low cost renewable energy solution that can serve the community.

II. Educational Component

This project was designed as a research project for undergraduate students to showcase renewable energy and its potential applications. Students were asked to construct a solar and hydrogen system that could meet the energy demand of portable electronics such as a cell phone. There are strong learning outcomes built into the development of this project including problem solving, critical thinking, communication, and team work.

This project was composed of three phases: **Phase 1** was the initial study, design, and validation of the system; **Phase 2** consisted of fabricating and testing the functionality of each component; and **Phase 3** includes detail integration and system optimization. Six student interns have been involved in these three phases of the project. In every phase, students worked individually and as a team, which they met frequently. Within each phase, critical thinking is required to solve problems arose from single component or during integration. During the learning processes, students prepared presentation and posters to present their finding and results to laboratory members and all staff and students in symposium. Faculty and graduate staff spent significant time to mentor and coach these students to accomplish these research and educational goals. As a result of this training, all four senior student interns received engineering job offers before graduation.

III. Experimental - System Design

The system’s main components consist of a PEMFC, an array of photovoltaic panels, an electrolysis cell, and gravity-assisted storage tanks. Alongside there are various auxiliary components, which were employed to support the above systems, as illustrated in the power transmission diagram shown in Figure 1.

During phase 1, students learned foundational knowledge of fuel cell, solar, and electrolysis through instruction from laboratory and public resources. By surveying previously published literature, students learned about the basic components of the system as well as the current state of the technology. In parallel, students started to investigate voltage and current requirements for charging cell phones from different brands. After gathering basic information of the power requirement, the students were tasked to size each component. The fuel cell and electrolyzer were selected using the manufacturer polarization curve specifications. The solar panel array was selected based on the power requirements of the power electronics and the electrolyzer. Using standard performance measures, the key components were tested individually to ensure that they could meet their respective energy demands in the system. Bases on the results from each component, final draft of system design was proposed including power condition between components. Finally, the entire system was tested for its capability to charge a cell phone at any time of the day producing 2.5W of available power throughout a 24-hour period.

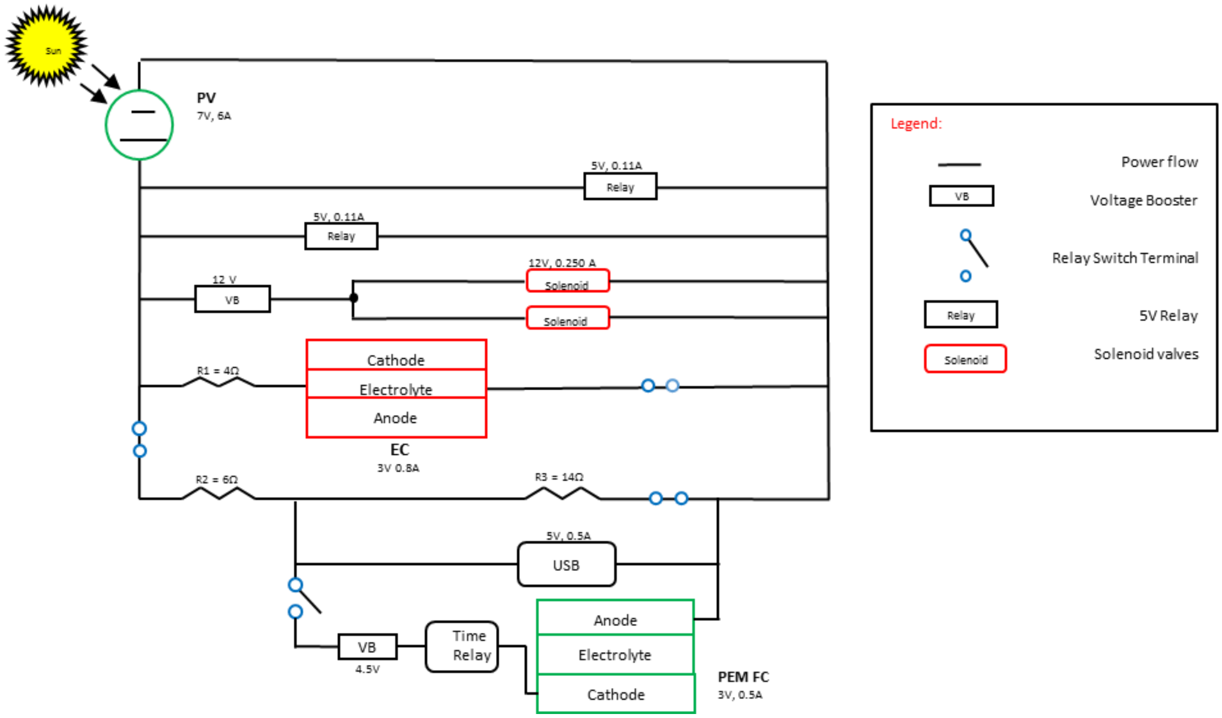

Figure 1. A schematic drawing of the overall system circuit diagram

This design switched between two modes referred to as the insolation and nighttime mode. Insolation mode operates when solar irradiance is sufficient, whereas nighttime mode operates when solar irradiance is insufficient. To switch between these two modes, relays and solenoids are installed to detect power output from PV and enable fuel cell operation. In either mode, cell phones can be charged using the most commonly used connection, USB 2.0 port (5 V, 0.5 Amps). The five-cell fuel cell stack from TDM is shown disassembled with materials labeled, in figure 2 (C & D) below. This stack is rated for 3 W. When the fuel cell stack is paired with a voltage booster, the power output can meet the requirement of the USB 2.0 port. Six photovoltaic panels produced by Voltaic Systems are rated at 6 W. The electrolyzer is a mini PEM electrolysis cell manufactured by Horizon Technology, which requires 3 W power input and produces 7 mL/min of hydrogen and 3.5 mL/min of oxygen. The hydrogen generated from the electrolyzer can fill our 1 L in-house designed hydrogen storage tank in 2 hours. The design of gas storage tanks consisting of graduated cylinders, rubber stoppers, and wash bottles was inspired by PHYWE Physics Laboratory Experiments.[12]

IV. System Integration

All components in the system were enclosed within a wooden frame with acrylic panels placed as windows. The fuel cell was sealed from the environment within an acrylic box to prevent contamination and over drying as shown in Figure 2 (B). Oxygen is fed into the box to provide required oxidizer during reaction. A similar idea was used by Shapiro with their “free to ambient” electrolyzer, which was kept within their hydrogen storage tank.[10] Six solar panels were connected in parallel and tilted to an angle of 30 degrees on the roof of this system for maximum sun light exposure. The electrolysis cell is directly coupled to these solar panels.

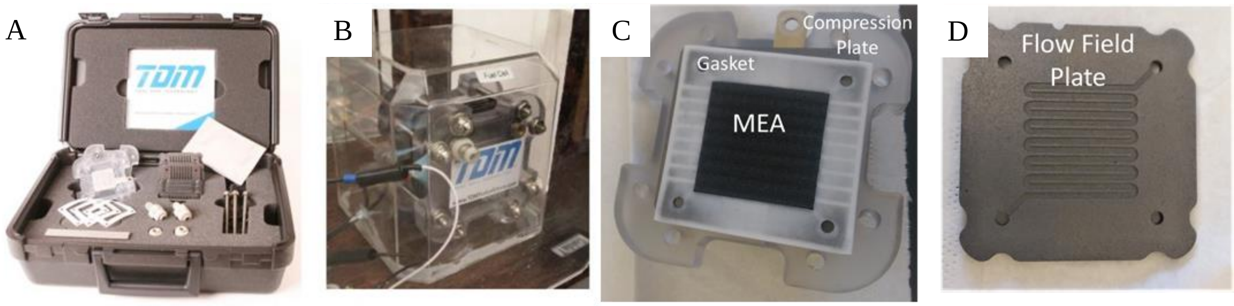

Figure 2. A box of the original TDM Flex Stak Fuel Cell stack (A) and integrated fuel cell system in an enclosed acrylic cover (B) Membrane Electrode Assembly (C) flowfield plate (D).

The details of our in-house designed gas storage system is illustrated in Figure 3. It contains two gas storage tanks: one storing hydrogen and the other storing oxygen. The hydrogen tank stores hydrogen generated from the cathode of the electrolyzer, while the oxygen tank stores oxygen from the anode. At the same time, deionized (DI) water is supplied to the electrolyzer from the bottom of the oxygen storage tank and its flow rate is controlled by a needle valve. Gas generated from the electrolyzer flow into corresponding tank from above and displace water into the top air bottle through the center connecting tube. During nighttime mode operation, the gas is pushed by the water in the air bottle (top) and flows to the fuel cell for electricity generation. This design stored gas at a pressure slightly above the ambient with no added components.

It also allowed for easy monitoring of gas volume based on water level in the storage tank.

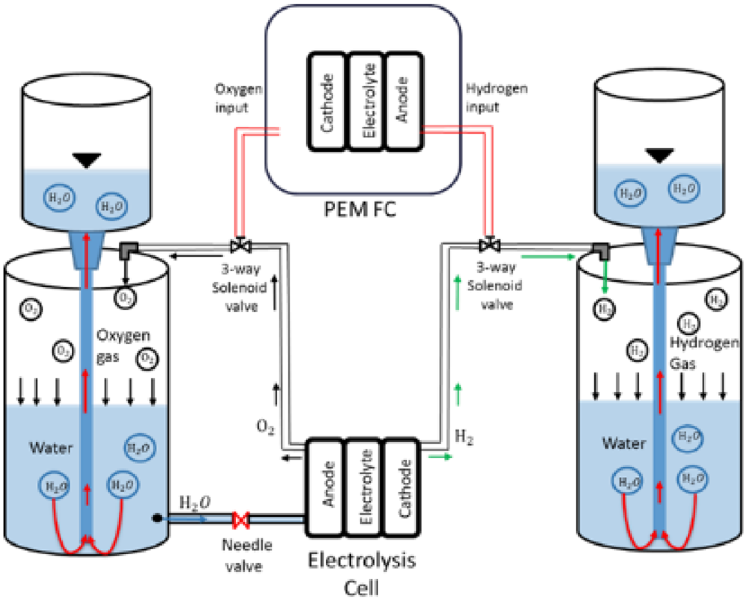

Figure 3. A drawing of the in-house designed gravity-assisted gas storage tank system.

In regard to electronic components, relays were chosen for the system to automate the transition between the PV and fuel cell power sources. Voltage boosters also had to be implemented in two places. The first one is to boost the fuel cell's output voltage to 5 V, while the second one is to boost PV voltage to operate the solenoids.

V. Testing

Performance testing of the five-cell open air fuel cell stack was completed on a standard fuel cell testing station produced by Greenlight Innovations. Stack operating conditions were 25°C, 100% anode Relative Humidity (RH), ambient pressures, 20 sccm of hydrogen flow, and open air supply to the cathode side through natural convection. Testing results were plotted in Figure 4 to be compared with manufacturer specifications. Actual stack performance started with minor deviation from factory specifications and deteriorated further with time. The initial deterioration in April at high current densities may have been a result of high heat exposure and lack of conditioning procedure. As shown in Figure 4, the cell voltage is nearly 0.5 V lower then factory specification at 6 mA/cm^2. The testing in July worsened drastically due to fuel cell contamination.

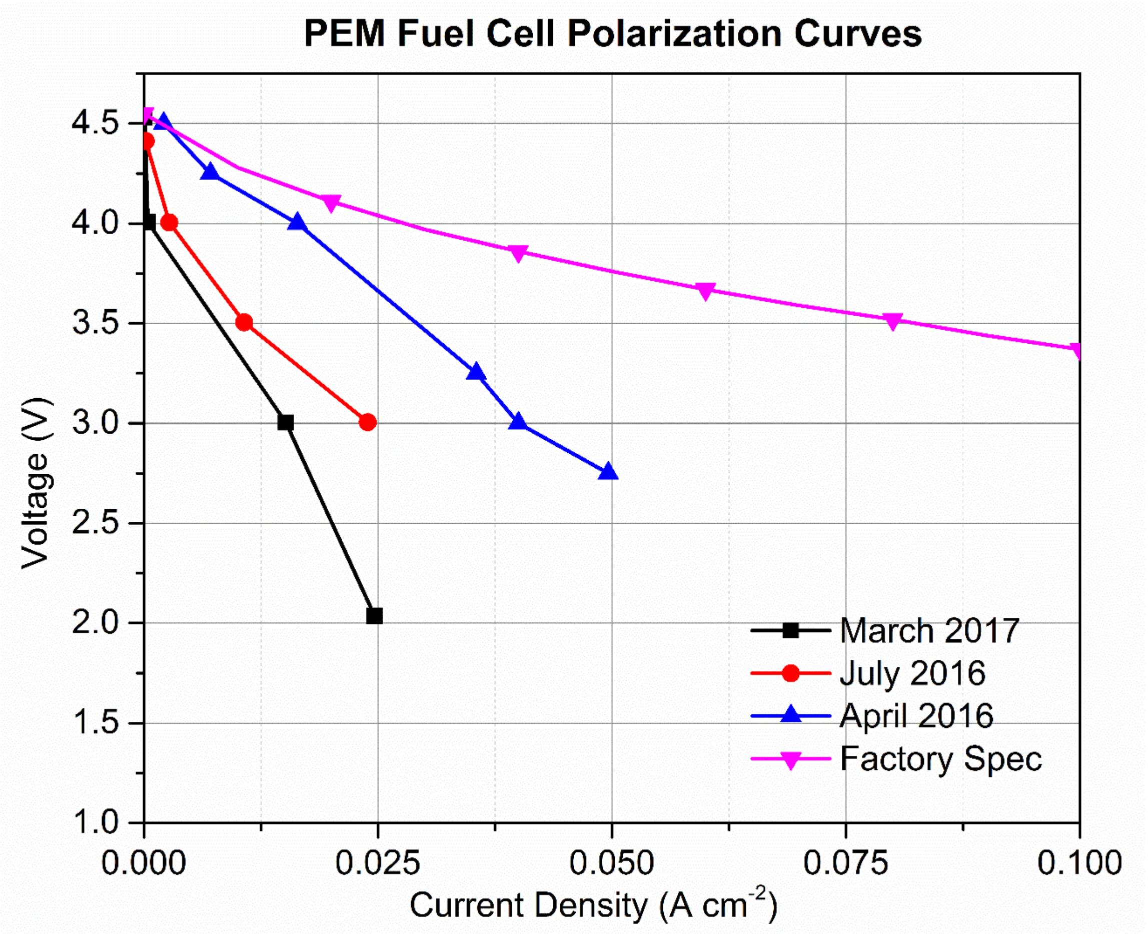

Figure 4. In-house tested fuel cell performance curves compared with the vendor specification. Operated at 25ºC, ambient pressure, 20 sccm anode H_2 100% RH, convection flow on cathode.

To test PV, each panel was brought outdoors, midday with clear skies, and was connected to a variable resistor. The panels were tilted to 30˚ as, this angle was calculated as the optimal annual performance solar panel tilt.[13] Resistance was set from 1 to 20 Ohms. A Fluke 117 Multimeter was used to measure voltage and current at each set resistance. Peak power output was near 4.5 W, which is less than the 6 W rated power. Through a parallel connection, the maximum power and current was 27 W and 5.4 Amps, which surpassed the requirements.

The electrolysis cell was tested for gas production rate. Power of just above 1 Watt allowed for the electrolysis cell to produce hydrogen and oxygen at its full capacity. Our test results showed that it took approximately two hours to fill the 1 L storage tanks. The storage tanks were tested to determine their leak rate. The tanks were filled with hydrogen at room temperature (25°C) and the amount of hydrogen lost was measured after 24 hours. The initial results indicted significant hydrogen leak. Improvements were made by applying silicon seal to the outer rim, where the stopper and the graduated cylinder were connected, and at the contact between the upper and lower tanks. After these modifications, hydrogen leak rate was reduced to minimal, which is sufficient for system demonstration.

VI Results and Discussions

After running the solar cells for a full day of insolation, the average and maximum power generated by connecting the six solar cells in parallel was 6.0 W and 9.0 W as shown in Figure 5 (A), respectively. The average power of 6.0 W is adequate to power the electrolyzer, cell phone and auxiliary components. Therefore, further testing was conducted to measure the voltage and current throughout the power range as shown in the right chart of the figure below, Figure 5 (B).

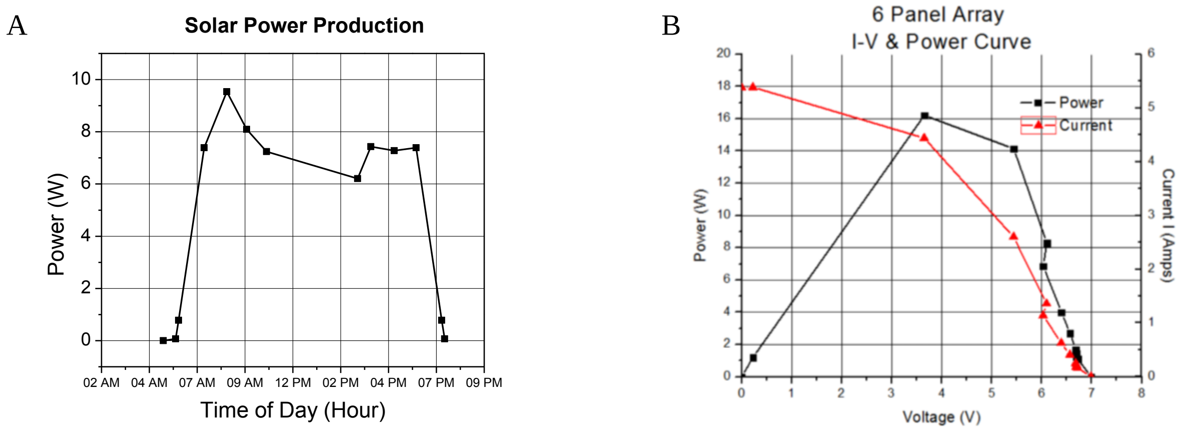

Figure 5. Power generation of the 6 parallel connected solar cells during a normal day at Merced (A) and current measurement (B).

During insolation mode operation, the electrolyzer consumed an average of 1.0 W for hydrogen generation and the cell phone charging consumed a power ranging between 0.8 and 1.4 W as shown in Figure 6. The total power requirement was less than 2.5 W, which is much less than the power generated by the 6 solar cells as illustrated in Figure 5 (B). This discrepancy provides an opportunity for further investigation of cell phone charging profile and system optimization.

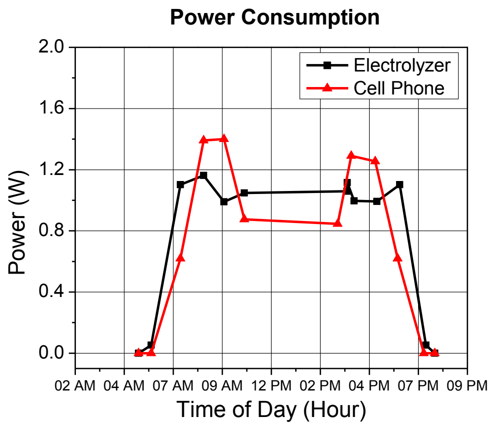

Figure 6. Power consumption of the electrolyzer (black) and cell phone (red).

After system integration, the fuel cell stack was tested again with the hydrogen supply from the hydrogen tank. The performance was further reduced from the initial testing due to contamination and could only generate 0.6 W as shown in the left Figure 7 (A) . The volume of hydrogen generated was measured as function of time as illustrated in the Figure 7(B). This 1.0 W water electrolyzer is capable of generating 800 mL in 2 hours. The overall integrated system successfully demonstrated its capability to charge cell phone under both insolation- and nighttime-mode operation.

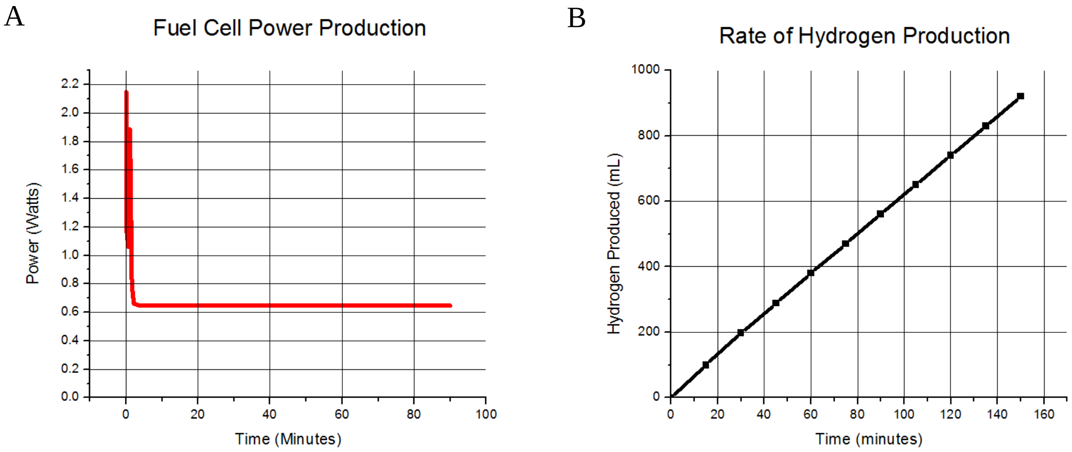

Figure 7. Power generation of the fuel cell stack (A) and hydrogen production rate (B).

Overall, the project fulfilled its intended purpose by giving students the opportunity to "learn by doing." Having worked from theory to practice, students developed their knowledge of fuel cells, photovoltaics, water electrolysis, and power conversion and condition. By testing the system components and sharing their findings with members in the laboratory, students gained capabilities in critical thinking, problem solving, communication, and team work. These technical and personal skills will greatly enhance their undergraduate experiences at University of California, Merced.

VII Conclusion

Through mentorship, students designed a regenerative cell phone charging system designed to be powered by solar cells, a water electrolyzer, and a fuel cell. To successfully integrate each component into the system, students studied and tested each component and the whole system. During insolation mode, solar cells generated electricity to charge the cell phone and power water electrolyzer for hydrogen generation. The six-solar cell array was able to output a maximum of 9 W, which was sufficient to satisfy the power demands of the electrolyzer (1.0 W) and cell phone (0.8 W). When solar energy was no longer available, the electric relay was switched to the fuel cell model. The designed power generation of the fuel cell was 3.0 W. However, the current fuel cell stack only generated 0.6 W.. This provides an opportunity for students to study and optimize this technology in the future. Further research will involve continuous electronic data collection to allow for better optimization. Although this integrated system is not yet fully optimized, it demonstrated the capacity to charge a cell phone under both day- and night-mode via renewable energy and provided the opportunity to educate undergraduates on the implementation of renewable technology.

VIII Acknowledgements

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