2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #39007

Efficiency Analysis of a Hybrid Solar System Design

Ryan Thomas Flynn
Caleb Holdridge
Alexandra Murphy
Ms. Jacquelyn Autumn Carter

Undergraduate electrical engineering student at the United States Coast Guard Academy.

Sarah Schollenberger
Prof. Tooran Emami Ph.D., United States Coast Guard Academy

Tooran Emami is a tenured associate professor of Electrical Engineering in the Department of Electrical Engineering and Computing at the U. S. Coast Guard Academy (USCGA). Her research interests are control and power systems, particularly Proportional Integral Derivative (PID) controller design, robust control, time delay, compensator design for continuous-time and discrete-time systems, analog or digital filter design, and hybrid power system design.

Efficiency Analysis of a Hybrid Solar System Design

Abstract

There are multiple parameters to study when measuring the performance and efficiency of Photovoltaic solar cells. This paper is a part of one-year capstone project results for undergraduate students in Electrical Engineering major. This capstone project focuses on maximizing the efficiency of a 100-Watt, 12V solar panel and studying its implementation in a hybrid power source system. Solar cell efficiency can be checked by measuring the power output, voltage-current characteristics, and environment in which the cell is placed. In the hybrid system, the solar panel will charge a battery. This project explains the importance of using a controller between the battery and solar panel, mainly the risk of overvoltage. One solution explored is using a Maximum Power Point Tracking (MPPT) charge controller that can prevent overvoltage by lowering the voltage of the solar cell to match the voltage of the battery. The solar cell output power is measured with a Mega 2560 Arduino and an INA219 current sensor connected to a light bulb load, a 12 V DC motor, and a 2.2k resistor attached. This project develops a DC-DC converter to run the loads with the battery banks charged from the solar cell. This project will also identify the relationship between temperature and irradiance on the effect of solar cell power output.

This project is suggested for experimental learning for senior-level undergraduate students. Students conducting this project will be expected to present how their findings compare to theoretical examples via status presentations, professional writing papers, and other assignments that can assess multiple ABET student outcomes. Throughout this project, the authors have shown how experimental learning has increased their awareness in many areas of electrical engineering as they encounter various issues within their experiments. Student takeaways from this project included noting the disparity between researched theoretical results and actual collected results, which varied greatly depending on conditions, the gravity of the economic and labor impact caused by solar panel installation, and the importance of data collection and precise instrumentation to ensure their collected results reflected accurate recommendations.

Introduction

Climate change is a prevalent global issue, as well as for the United States Coast Guard (USCG). With CO_2 emissions increasing by 28 percent in just one year, there has been a notable shift in efforts toward finding a solution [1]. This is especially important for the USCG given that the 11 USCG missions are heavily impacted by the environment, meaning that changes in the climate can drastically affect the responsibility of assets across the US. With these considerations, renewable energy sources have gained increased attention to solve the climate problem.

Photovoltaic or solar cells are one of the major renewable energy sources and have been extensively studied by engineers to maximize power output due to their high utilization rate. The Output of a solar cell depends on the cell temperature and the amount of solar irradiation that reaches the cell. Engineers have modeled solar cells' solar orbit and position overall times worldwide to determine optimal solar irradiation [2]. For achieving optimal cell temperature, the material parameters of the semiconductor, such as cell thickness and material type, have the most significant effect on performance [3]. Another critical factor that significantly impacts solar cell efficiency is the ratio between sunlight power input and its power output, which is one of the most important characteristics when implementing solar cell systems. Solar energy efficiency depends on the solar panel's tilt in relation to the sun. Currently, two forms are consistently used to optimize the tilt angle to gain the most power. One way to optimize the power is to calculate the optimal tilt angle for the location of the solar panel in relation to the sun; this was calculated to be 41° for the system with an adjustment of 15° less in warmer seasons and 15° more in cooler seasons [4]. The other system is to use continuous adjusting to consistently optimize the power received by the system [4]. A current system is being implemented in residential areas within the US to calculate the time intervals for tilt adjustments as well as the angle at which the tilt should be. [4] The optimal tilt angle was used to develop the most efficient system in this system. The United States Coast Guard Marine Safety Center plans to create a policy for hybrid green ships that use this technology as a power source in the near future, so it is essential for future Coast Guard officers to study the factors that go into the solar cells and how they would be implemented on a hybrid green ship. Researchers have defined the benefits of using electric power on boats as a maintenance fee reduction capability, increased safety with less fuel on board, and zero greenhouse gas emission [5]. With this potential increase in safety and cost, more boating and shipping companies will continue to transition to partially or fully electric each year, creating the need to understand these hybrid systems.

In the Department of Electrical Engineering and Computing for Electrical Engineering major, most student outcomes are evaluated in Capstone 1 and 2 courses. In addition, multiple program educational objectives for the ABET Criterion 3 are assessed in the fall and spring semesters for the senior students.

This paper focuses on maximizing the efficiency of a 100-Watt, 12V High-Quality Solar Technology solar panel and its system characteristics. The second part of this capstone project includes using solar panels in a hybrid power system with a battery and hydrogen fuel cell. In the current paper, first, solar panel modeling in MATLAB is presented. Then the experiment experimental solar panel is implemented. Next, the battery life analysis and proof of concept are discovered. After that, the paper's conclusion is presented. Finally, the student outcomes are summarized in the last section.

Solar Panel Modeling In MATLAB

The simulated modeling of the solar panel in MATLAB Simscape utilizes the voltage and current characteristics. In this software, the characteristics and behavior of the solar cell can be studied while varying its connections and conditions. For example, some aspects are changing the arrangement of solar cells or altering the temperature or amount of solar irradiance absorbed by the system to see the solar cell's response. Simscape has a solar cell block that can represent the 100-Watt, 12V solar panel, as shown in Figure 1.

The solar cell block in Figure 1 represents a solar cell current source that includes adjustable features such as solar-induced current, temperature dependence, predefined parameterization, and a thermal port. This block can connect to a solver configuration block in Simscape which can solve for output current based on the temperature and amount of irradiance. Also, this block's parameters can be set as open-circuit voltage and short-circuit current in the program, which in this case are 24.3V and 5.5A. In the Simulation in Figure 2, inputs with solar irradiance and temperature were implemented into the solar cell block in Simscape. There was a current sensor set up in series with the solar cell block and a voltage sensor in parallel to measure the current/voltage characteristics of the solar cell block. The scope blocks were used to plot the solar cell's power characteristics, as shown in Figure 3. This plot shows that the maximum power for the solar panel simulation is at 6.286 A, where the voltage is at 0.7 V.

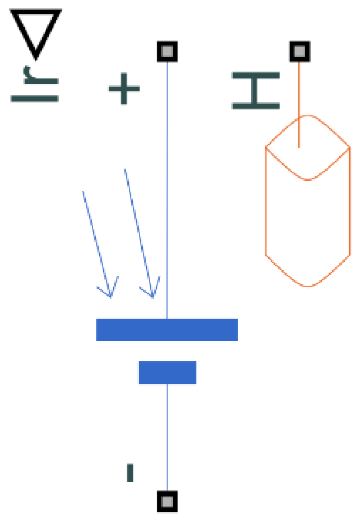

Fig. 1. Simscape Solar Cell Block

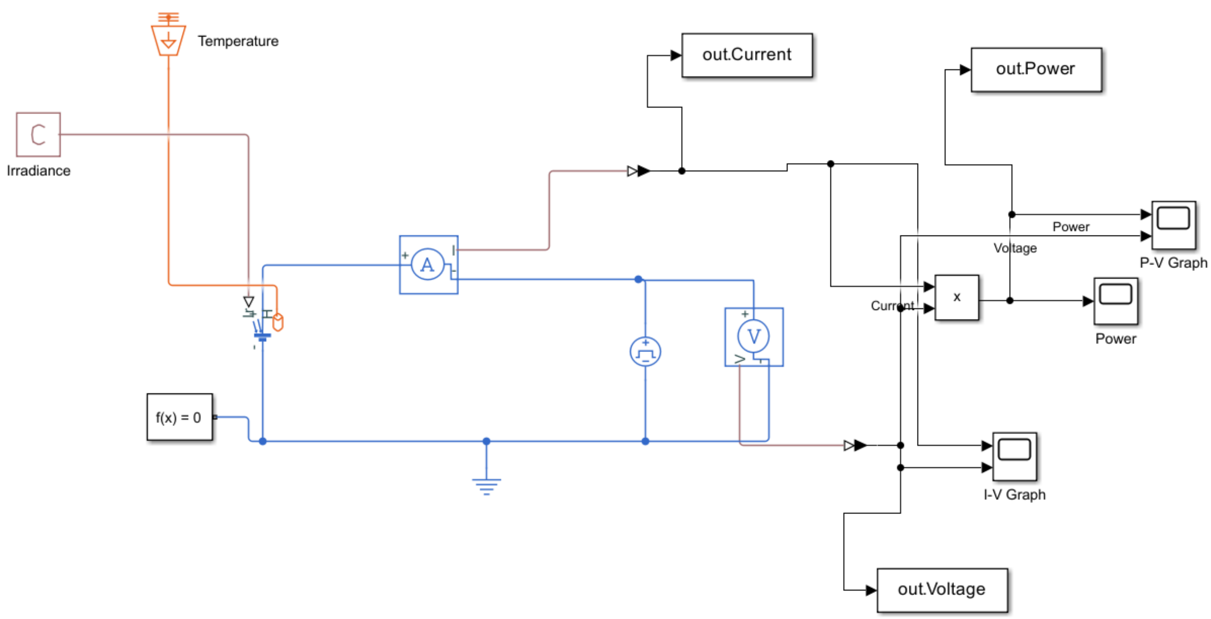

Fig. 2. Simulink Model of Solar Panel

These are the two plots received from the SimScape simulation, which represent the current and voltage characteristics of the solar panel with 1200 W/m2 irradiance and 60 degrees Fahrenheit. The effect of solar irradiance and the temperature of the solar panel on the power output is displayed in Figures 4 and 5.

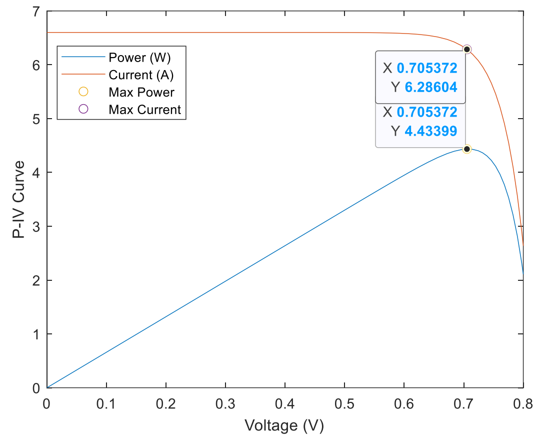

Fig. 3. Output power of the Solar System

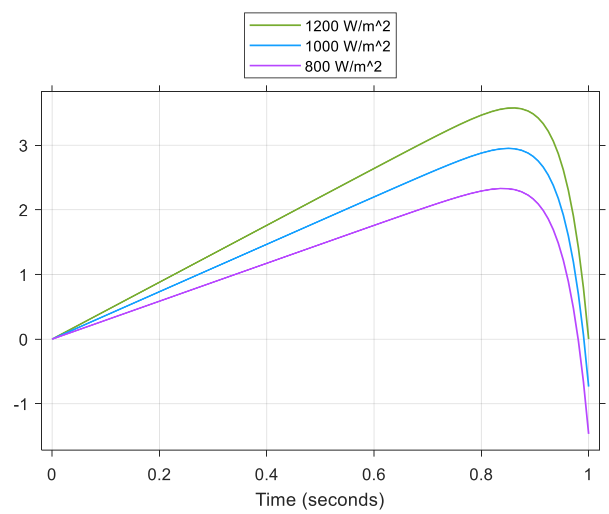

Fig. 4. Effect of solar irradiance on power output

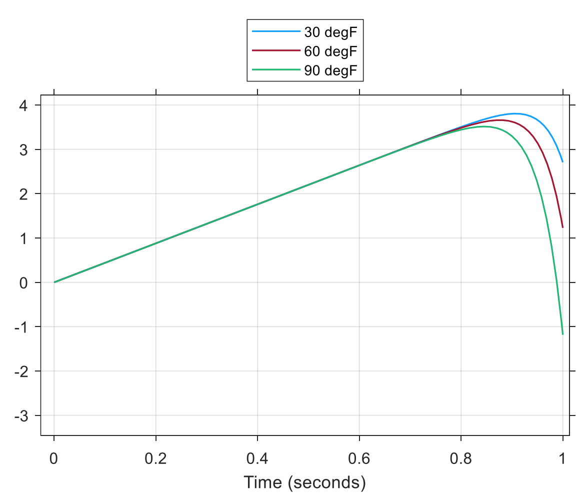

Fig. 5. Effect of temperature on power output

Experimental Solar Panel

The solar panel was tested by measuring its ability to charge a 12V battery. The panel is a 100W, 12V solar panel with current-voltage characteristics of 24.3 V for open-circuit voltage and 5.5 A for short-circuit current. To measure the output of the solar panel, an INA-219 current sensor with a max ampere of about 5 A was utilized when the solar panel current outputted to a 2.2k resistive load. In addition, the Mega2560 Arduino board was applied to collect measurements through a laptop connection. The setup is shown in Figure 6, and the data throughout a morning period on November 10, 2022, is displayed in Figure 7, with power measured in watts (W), current measured in milliamps (mA), and voltage measured in volts (V).

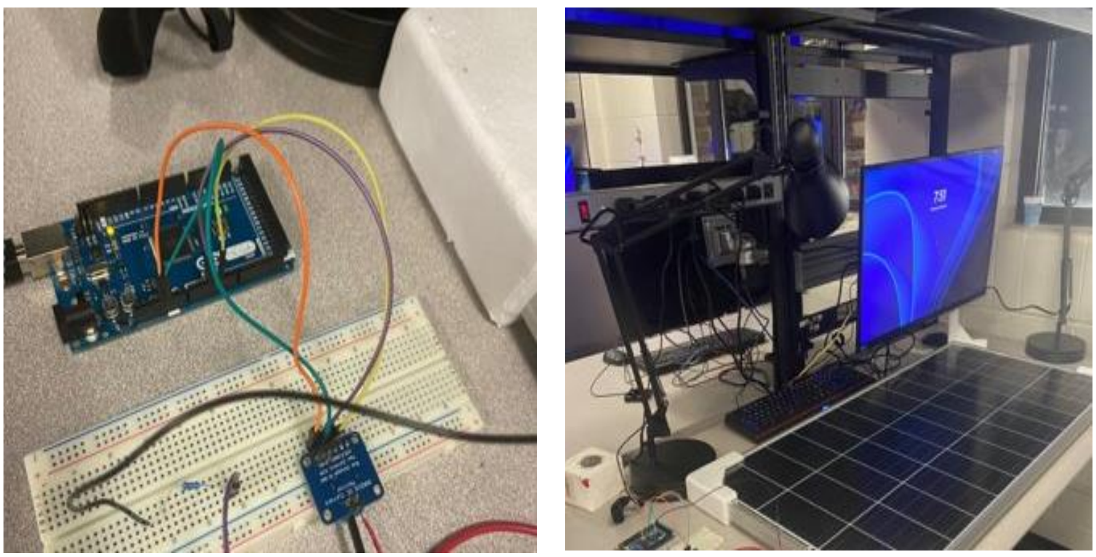

Fig. 6. Arduino Setup with Solar Panel

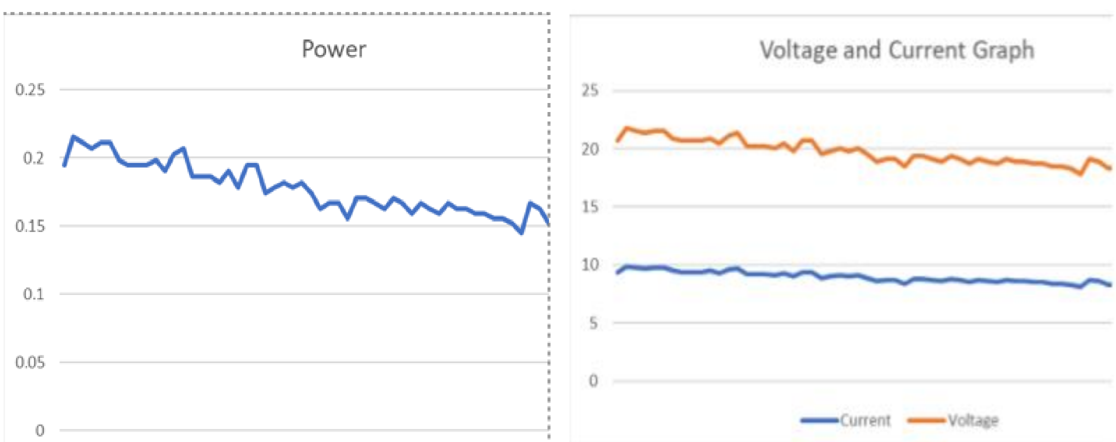

Fig. 7. Output of Experimental Solar Panel

The next step is to connect the solar panel to the 12V battery and collect its data via the Maximum Power Point Tracking Algorithm Charge Controller, which measures the battery's voltage and solar panel to prevent overvoltage of the battery. Then, the modeling and experimental data we receive can be applied to illustrate the maximum power a solar panel can output while also considering various environmental factors for hybrid green ships in the future.

The Maximum Power Point Tracking (MPPT) approach is applied to extract the maximum generated power from a photovoltaic system. The maximum power point can be achieved by connecting an adaptor, such as a DC-DC converter, to extract power to a load. The MPPT algorithm controls the "loading" or impedance of the photovoltaic cells required to keep the system around or near the maximum power point. The total power depends on various values of temperature and solar irradiance. The MPPT approach uses the Incremental Conductance principle to deduce the maximum power point by measuring and comparing the conductance and incremental conductance and adjusting the duty cycle based on this comparison to achieve optimal voltage for maximum power. If conductance is smaller than the opposite of incremental conductance, the duty cycle is increased in the MPPT algorithm to approach maximum power point and vice versa [6].

Battery Life Analysis and Proof of Concept

The Life P04 12V/8Ah Lithium Iron Phosphate Battery will be utilized for the overall system in conjunction with the solar power system. The battery offers a sufficient storage capacity for the energy produced from the solar panel while also supplying an adequate output for the demand of the load. The charge and discharge characteristics are found in the battery's specification sheet and can help provide knowledge of how to use the battery as a power source in the overall system [7]. However, further analysis needed to be completed to optimize the battery's use for the longevity of battery life and the overall system performance.

The LifeP04 12V/8Ah battery requires a long period of time to discharge and charge. Therefore, the team decided to work with a small-scale battery system to learn about a battery's charging

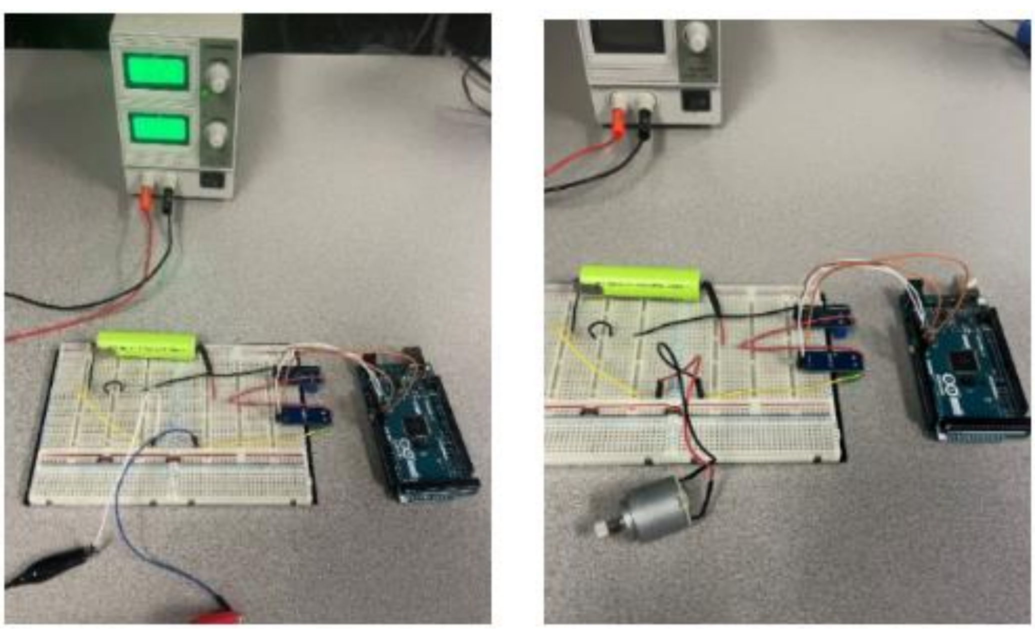

Fig. 8. Battery Circuit

and discharging state. A Tenergy 3.7V/2600mAh was initially utilized because of its smaller charge and discharge times [8]. This allowed the battery's output data to be efficiently collected. The proof of concept for collecting the battery's outputs utilized a circuit with Arduino components reading data into Matlab. Figure 8 shows the completed circuits, with the left used for charging and the right for discharging.

The circuits were constructed similarly, utilizing the Tenergy battery, an Arduino Uno, and voltage and current sensors. The difference is that when the battery was being charged, a DC power supply was utilized to make the battery the load, and when the battery was discharging, a DC motor was utilized to draw power and act as the load. The Arduino sensors read the battery's output data into MATLAB, which collected the data and plotted the voltage and current of the battery over time.

In real-time, a plot of the current and voltage readings from the Arduino microcontroller is generated. While the code runs, the plot continually updates to display the elapsed time and present current and voltage outputs. Once the code stops, the plot closes and can be saved. Sample plots of the discharge and charge cycles of the Tenergy 3.7V/2600mAh battery are shown in Figure 9.

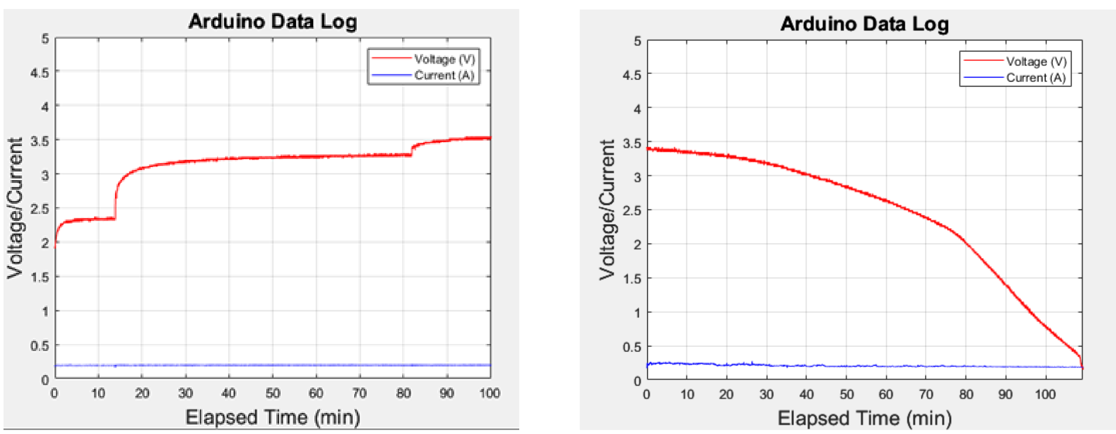

Fig. 9. Charging (Left) and Discharging (Right) Diagrams for Tenergy Battery

The plots demonstrate that this method of collecting the output voltage and current of the battery is successful. The discharge plot is consistent in that the battery voltage decreases with the time the battery is used. The current also remains constant due to the load staying the same and the battery operating with a constant current. However, it does not correlate to the battery's specification sheet with the time it remains at its max voltage. The charge plot is not as consistent, but this is due to the DC power supply having to be adjusted over time to charge the battery to its full potential. However, once this is applied to the overall solar power system with the battery connected to the MPPT charge controller, a consistent charging voltage is expected. With these considerations, the overall objective for the proof of concept was met, and a plan for collecting and plotting the battery's current and voltage outputs through the charge and discharge cycles was established. Through additional trials, more accurate plots can be created for the Tenergy 3.7V/2600mAh battery, but this is not a requirement since the LifeP04 12V/8Ah will be used in the overall system.

There are multiple avenues where the proof of concept and collected data can be applied to the LifeP04 12V/8Ah battery in the overall solar power system. Another possibility is scaling the collected data to the overall system size. Both means would allow for a better understanding of how to optimally switch from the battery to the hydrogen fuel cell for powering the load. However, the first solution is more accurate but less time efficient because the switching would be determined from the characteristics of the utilized battery instead of scaled ones from a different kind of battery.

The duration of time it takes to completely discharge the LifeP04 12V/8Ah battery can be calculated from the battery's capacity and current being drawn. However, considerations need to be made if the lifespan of the battery is taken into account. It is advantageous to only discharge the battery to its rated 12V value to prolong the charge and discharge cycles the battery can be used for. With this, the previously established proof of concept to analyze the battery's output voltage and current must be applied. The circuit setup is shown in Figure 10.

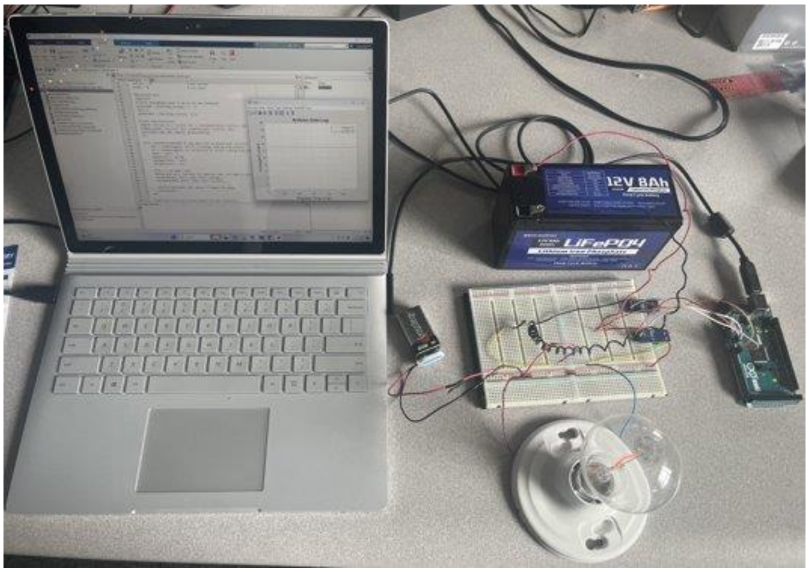

Fig. 10. LifeP04 Battery Analysis Circuit

The circuit was constructed similarly as previously shown, except a 200W lightbulb was utilized in exchange for the DC motor. The laptop is running MATLAB to collect and plot the voltage and current outputs from the battery through the means of Arduino voltage and current sensors taking readings into the Arduino board. This setup allowed the team to understand how to incorporate the LifeP04 battery into the overall system. The MATLAB discharge plot for the battery is shown in Figure 11.

Through this trial, the lightbulb drew 0.7A from the battery until the battery reached an output voltage of 12V. The plot shows that the battery can be operated for seven hours and thirty minutes before needing to be recharged to preserve its longevity and future use. This gives a framework for its use in the overall system because the duration of operating is now known, along with when the overall system should switch to the hydrogen system to power the load.

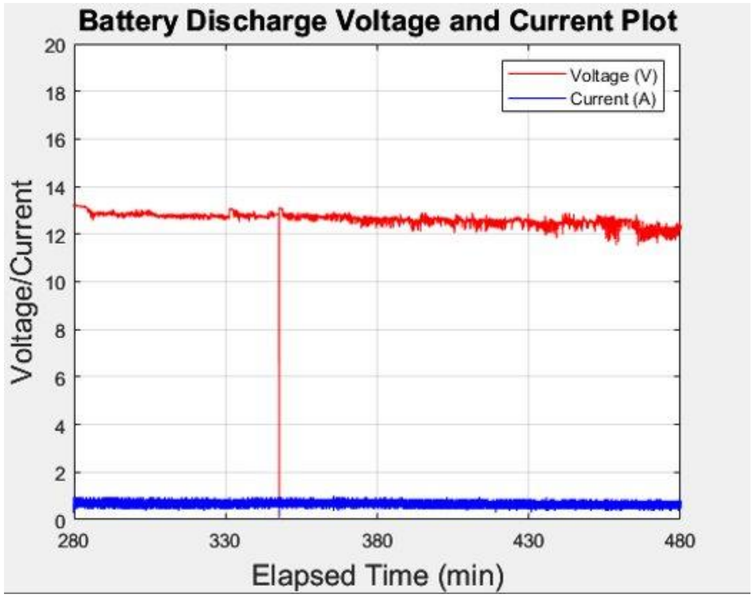

Fig. 11. LifeP04 Discharge Plot

Conclusion

In this paper, multiple parameters were studied to measure the performance and efficiency of Photovoltaic solar cells. This paper focused on maximizing the efficiency of a 100-Watt, 12V solar panel and studying its implementation in a hybrid system. Solar cell efficiency was determined by measuring the power output, voltage-current characteristics, and environment in which the cell was placed. In the hybrid system, the solar panel charges the battery. This project discussed the controller between the battery and solar panel, mainly the risk of overvoltage. One solution explored for the Maximum Power Point Tracking (MPPT) charge controller was that it could prevent overvoltage by lowering the voltage of the solar cell to match the voltage of the battery. The solar cell output power is measured with a Mega 2560 Arduino and an INA219 current sensor connected to a light bulb load, a 12 V DC motor, and a 2.2k resistor attached. This project developed a DC-DC converter with the battery banks charged from the solar cell to run the loads. This project identified the relationship between temperature and irradiance on the effect of solar cell power output via MATL.

As renewable and hybrid technologies improve, more remarkable instances will be where solar cells and rechargeable batteries are implemented commercially. With an increased understanding of the factors that affect solar cell efficiency, solar cells can be more effectively applied to hybrid systems, including battery systems. Implementing a controller when charging batteries is critical to maintaining the batteries' integrity and ensuring longevity. Renewable technology can always be improved, but implementing the available products is essential to slowing climate change, and knowing how different factors affect solar cells and batteries can aid in optimizing a hybrid system.

Student Outcomes

The solar photovoltaic system was assessed in the capstone course through various assignments relating to the environmental and economic effects of solar panels. One assignment considered the multiple options for installing different types of solar panels regarding their efficiency and cost. Students learned that there is a positive correlation between solar cell efficiency and economic drawbacks, which illustrates the complexity of implementing this renewable energy source. In the capstone course, there were several suggestions for the improvement of the solar system model, which included incorporating a battery or load into the model to collect theoretical results. The SimScape model of the solar system found was difficult for students to establish a fully connected solar system that charged the battery and was concluded to be foundational learning for how a solar system should work under varying solar irradiance and temperature conditions. Some accommodations that can be made for students with a lack of equipment or funding for projects include purchasing smaller solar cells, which can illustrate solar cell characteristic graphs to understand the effects of solar irradiance and temperature on solar output. Small-scale lamps and batteries can be used to meet the economic disadvantage of students to explore differing solar systems when charging or discharging a battery.

In the Department of Electrical Engineering and Computing, the following student outcomes assess in Capstone 1 and 2 courses to support some of the program educational objectives for the ABET Criterion 3 in the fall and spring semesters.

1. "an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
2. an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.
3. an ability to communicate effectively with a range of audiences.
4. an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.
5. an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies. [9]"

References

[1] L. Lakatos, L., F. Hevessy, J. Kovács, J.: "Advantages and disadvantages of solar energy and wind-power utilization," *World Future*,67:6, pp. 395–408, 2011.

[2] C. Ying-Pin and S. Chung-Huang, "Effects of the Solar Module Installing Angles on the Output Power," *International Conference on Electronic Measurement and Instruments, ICEMI*
Xi'an, China, 2007, pp. 1-278-1-282, doi: 10.1109/ICEMI.2007.4350442.

[3] S. Hungyo, K. J. Singh and R. S. Dhar, "Cell thickness optimization of dual junction InGaP/GaAs solar cell against temperature variation," *2019 Devices for Integrated Circuit (DevIC)*, Kalyani, India, 2019, pp. 281-285, doi: 10.1109/DEVIC.2019.8783736.

[4] C. P. Leung and K. W. E. Cheng, "Zero emission solar-powered boat development," *2017 7th International Conference on Power Electronics Systems and Applications - Smart Mobility, Power Transfer & Security (PESA)*, Hong Kong, China, 2017, pp. 1-6, doi: 10.1109/PESA.2017.8277736.

[5] S. Akhlaghi, H. Sangrody, M. Sarailoo, and M. Rezaeiahari, "Efficient operation of residential solar panels with determination of the optimal tilt angle and optimal intervals based on forecasting model," *IET Renewable Power Generation*, vol. 11, no. 10, pp. 1261-1267, May 2017, doj: 10.1049/iet-rpg.2016.1033.
[6] N. Harrabi, M. Souissi, A. Aitouche, and M. Chaabane, "Modeling and control of photovoltaic and fuel cell based alternative power systems," *International Journal of Hydrogen Energy*, vol. 43, no. 25, pp. 11442–11451, Jun. 2018, doi: 10.1016/j.ijhydene.2018.03.012.
[7] "Life_04 Lithium Iron Phosphate User Manual," cdn.shopify.com. https://cdn.shopify.com/s/files/1/0253/9752/6580/files/12V8ah_10ah_20ah_30ah_50ah_lithium_battery.pdf?v=1673075848 (accessed April 06, 2023).
[8] "Lithium-ion Rechargeable Battery," Tenergy Corporation, Fremont, CA, Jan. 2017. Accessed:2022.[Online].Available:https://www.shorepowerinc.com/media/wysiwyg/files/tenergy/msds/Tenergy-Li-ion-MSDS.pdf.
[9] https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2022-2023/.