Spring 2023

Revolutionizing Solar: A Portable Solar Solution for Anywhere, Anytime Use

Shelby Powers

Revolutionizing Solar

A Portable Solar Solution for Anywhere, Anytime Use

Written by Shelby Powers

Collaborated with Kai Parkinson and Sarah Jackson

Abstract

Solar panels have been growing in popularity among residential consumers. There are many different options available, but presently small-scale solar systems are limited. Due to this, access to renewables for those living or working in small spaces is difficult. In addition, costs related to the purchase and installation of solar panels are high, providing another barrier to wide-scale residential solar energy usage. These are the issues that the project discussed in the report addresses.

The project discussed here is batter-based renewable power supply. This works by charging a battery using a photovoltaic, or solar, panel so that the user can attach a load that can be powered by the battery. The major components are the 50-Watt solar panel, the two 12-volt sealed lead-acid batteries, DC-DC power converters, USB ports for power for the user, and LCD screens to display important information. The main design goal was to create a compact system that can go anywhere without any permanent installation process. The focus of this report is on the code and related hardware required to successfully complete this project.

Table of Contents

Background

In a world of growing awareness of environmental impacts, green alternatives are becoming increasingly popular. However, many systems require permanent installations of solar panels to be made, and these installations are expensive. According to the Pew Research Institute, in 2019 around 36% of US households were renters [1], which limits their ability to make these investments and permanent installations. The only way these people can install solar panels is if their landlord allows the installation, limiting access to this technology. Another limitation is the price of conventional rooftop solar systems, which cost on average around $12,000, about one-fifth of the US median household income [2][3][4]. These high costs limit many seeking to utilize more green energy sources.

These challenges were the inspiration for this project. Upon completion, the battery-based solar system will offer a compact, impermanent, and inexpensive way for consumers to utilize solar energy for personal use. The entire design is compact, making this system great for apartment or office use, or for anywhere small amounts of electricity are used. The scope of applications is somewhat limited, but the final product will allow users to charge small devices like phones or smartwatches and power loads, such as USB-powered fans or lights.

Project Overview

The overall scope of this project is much larger than discussed in this report. The system block diagram, in Figure 1, shows the main connections of the design. The output of the solar panel is fed through the maximum power point tracking (MPPT) converter, which controls the voltage at the panel. The current is controlled by the charge controller which is then connected to one of the two batteries. Either one of the batteries can be powering the microcontrollers, but only one is connected at a time, controlled through a physical switch that the user must flip. The microcontrollers output information and messages to two LCD screens for user information. The primary battery has connections to the three load converters, of which only one will ever be on at a time.

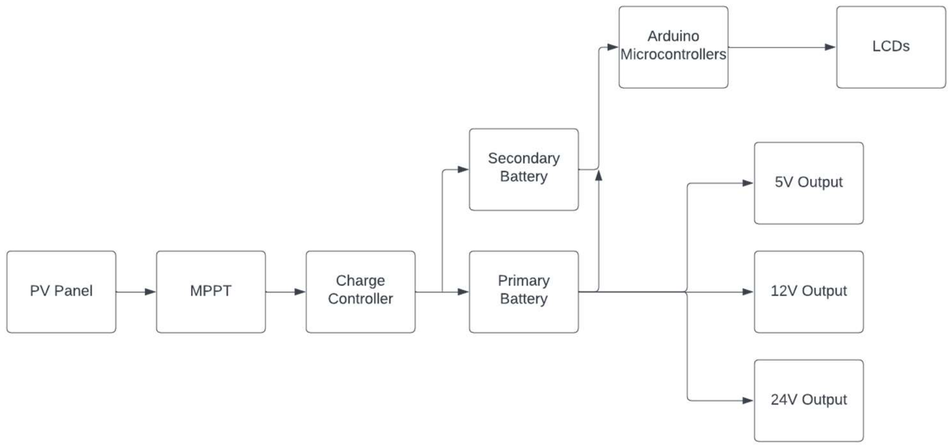

Figure 1: Basic system flow diagram

The focus of this report will be on the code behind each component of the system, excluding the battery state-of-charge (SOC) code. The flow diagrams and overall operation of the code is discussed.

The physical circuit components and subcircuits are just as important for this project and will be briefly discussed now. A 50-Watt solar panel is used, chosen for its small size to meet the design goal of a compact system. The MPPT converter is a buck circuit whose switch is controlled by the PWM output of the Arduino. The output of the buck is fed into the charge controller circuit, which is also a buck converter. Instead of voltage, this converter will mainly be regulating the current fed into the battery. The connections to the batteries have switches that control which battery is receiving this current, though the physical switch is needed to switch connection to the microcontroller. The primary battery is the only one connected to the loads. The voltage is stepped down using another buck converter for the 5-volt output only when the user selects this port using the switch. The 12-volt output is regulated using a linear regulator to maintain the voltage, and again only runs when the user selects this output. For the 24-volt output, a boost circuit has been constructed to increase the voltage, and only runs when this port has been selected by the user.

Components

There are many physical components that are used for this project, the most important being the 50-Watt solar panel. There are the converter components of capacitors, inductors, MOSFETs, and gate drivers. In addition, there are other components, such as mechanical switches and breakers, that are focused on user and component safety. These are important for the final project but are outside the scope of this report. Working alongside these components is code that controls each aspect of the project. To aid in this are more components, including the microcontroller running the code. These microcontrollers use information from voltage and current sensors, and control switches throughout the circuit in response to sensor data. There are then LCDs that display important information for the user.

Microcontrollers

For this project, two Arduino Leonardo microcontrollers are used to control aspects of the circuit. These microcontrollers serve as the control of the project, receiving important information and responding accordingly. Arduinos are used because they are easy to code and have built-in analog, digital, and PWM pins, all of which are necessary for this project. The Leonardo model was chosen because it has 12 pins that can read analog signals, twice as many as other models of Arduino microcontrollers. The most important functions of the microcontrollers are gathering sensor data, controlling the switches throughout the circuit, and displaying pertinent information on the LCDs for user information.

Sensors

The voltage sensors used throughout the circuit were constructed out of resistors. These resistors act as a simple voltage divider, stepping the voltage down, and were selected to be large enough in value to minimize current flow. The analog pins of the microcontroller can only receive up to 5 volts as an input; anything more risks damaging the pin and therefore making it unusable. These sensors step down every voltage value to fit within this range, with extra tolerance built in for voltages that slightly exceed expected values. There are three different sensor ranges, which take inputs up to 6 volts, 15 volts, and 24 volts, as shown in Figure 2. The 0-6 volt sensors are used for the mechanical switch voltages, to tell which position they are in at any point. There is also a sensor on the output of the 5-volt outlet, and the voltage is displayed on the LCD. The 0-15 volt sensors are used to monitor the battery voltages and the voltage on the 12-volt outlet, which should never exceed 13 volts. Finally, the 0-26 volt sensors are used for monitoring the 24-volt outlet and the solar panel voltage, neither of which should exceed 25 volts at any point.

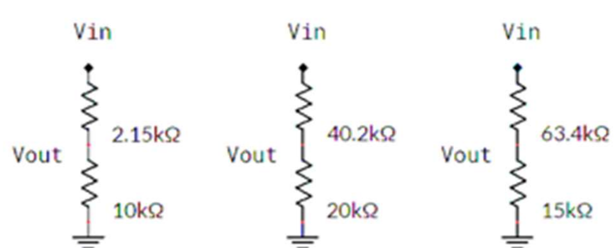

Figure 2: Schematic of voltage sensors: 0-6V, 0-15V, 0-26V respectively

There are also ACS712 current sensors at each stage of the circuit. These 5 Amp sensors were purchased and have been placed at critical points. They monitor the current from the solar panel, the current into each battery, current to the microcontrollers, and the current to the loads. Since they are Hall Effect sensors, they way they measure current is by measuring the strength of the magnetic field produced by the current flowing through the wire. There are several components in the circuit that also induce a magnetic field, so when the sensors are close to the inductors the magnetic fields cause interference that impacts the current reading. As such, careful measurements were taken and an appropriate offset was added for each sensor to make them as accurate as possible.

Switches

There are many switches throughout the circuit in addition to the mechanical switches described earlier. These switches control the current throughout the circuit. Opening them prevents unwanted current flow, providing extra safety for the batteries, other components, and user. There are switches controlled by the microcontrollers before each battery to prevent unwanted current from flowing into the batteries. There are also switches after the primary battery to prevent the loads from drawing current from the battery when it is at a very low state of charge. There are also switches before each output circuit, which prevents unnecessary voltages on the outlets for user safety and power conservation. The switches are opened and closed using a digital signal from the Arduino in response to information from sensors and batteries.

In each of the constructed buck and boost circuits are MOSFETs that switch rapidly on and off in response to signals from the microcontroller. This frequency at which the switching occurs is 20 kHz, which is the frequency at which the physical components, the capacitor and inductor in each circuit, filter out all but the DC component of the output signal, providing a smooth voltage and current. PWM signals are sent by the Arduinos to gate drivers, which are connected to the MOSFETs. The duty cycle of this signal is determined in the code and is changed in the appropriate direction to achieve the desired result on the output of the converters. When the converter is not being used, the switch is left open for safety.

LCDs

The LCD is an important part of this project. One of its most important roles is giving messages to the user. When the batteries need to be switched for charging, a message will appear asking the user to flip the switch. This message will not disappear until the correct battery is connected for charging, which is monitored by the microcontroller. There is also an error message that displays when the system is in its error state, notifying the user that an error has occurred. This lets the user know that an issue has arisen, and they can choose to restart the system or start repairs.

Another useful aspect of the LCDs is that they display useful information about the state of the system. Since there are two microcontrollers, there are also two LCDs, which display different information. One LCD displays which of the two batteries is charging, whether the primary battery is capable of powering loads, and the SOC of each battery. The second LCD shows voltage, current, and power from the solar panel, along with any loads that are connected. If there are no loads connected, then this is displayed as well, along with whether any loads connected will be powered. With this information, the user can monitor the power output of the solar panel, along with the power draw of their own devices.

Algorithms

In addition to the physical components of the circuit, the algorithms running on the microcontrollers are crucial to the success of the project. All the algorithms discussed were created from scratch, with their own built-in safety mechanisms. The MPPT and output algorithms are on one microcontroller, along with the appropriate display code. The other microcontroller holds the charge controller, SOC (not discussed in this report), system state, and display code.

MPPT

The first major component of the project is the MPPT converter, whose PWM signal is controlled by the microcontroller. The circuit is a buck converter, stepping the voltage of the solar panel down to get maximum power transfer to the rest of the circuit. This is necessary because of the characteristics of the solar panel. The I-V curve displaying these characteristics is shown in Figure 3. As the irradiance from light hits the panel, the current from the panel changes, but remains constant for different voltage levels.

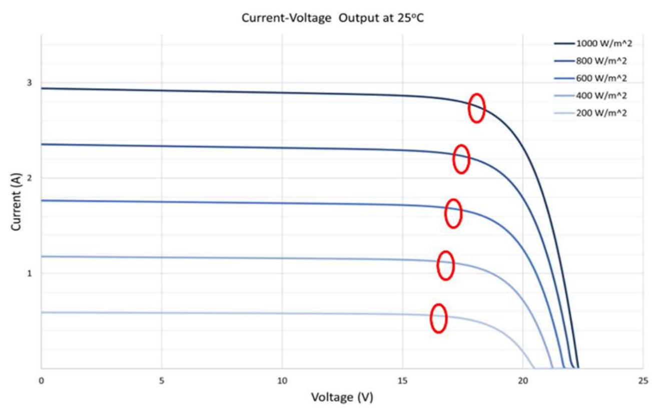

Figure 3: I-V curve for solar panel used in this project

This is why the buck controller is necessary, to control the voltage at the solar panel so that the maximum power point, shown circled in red for each irradiance curve, is achieved. As shown in the graph, this voltage is below the full open-circuit voltage, which is why the buck is used to decrease the voltage at the panel.

The algorithm itself uses these properties to determine which direction the duty cycle needs to change to find this maximum power point. When the power from the solar panel changes, the algorithm checks the power value against the last saved value. From here, the algorithm checks the measured current value against the last saved value. This determines whether the I-V curve has shifted up or down from its previous state. This determines whether the duty cycle needs to increase or decrease to find the maximum power. The basic flow chart is shown in Figure 4.

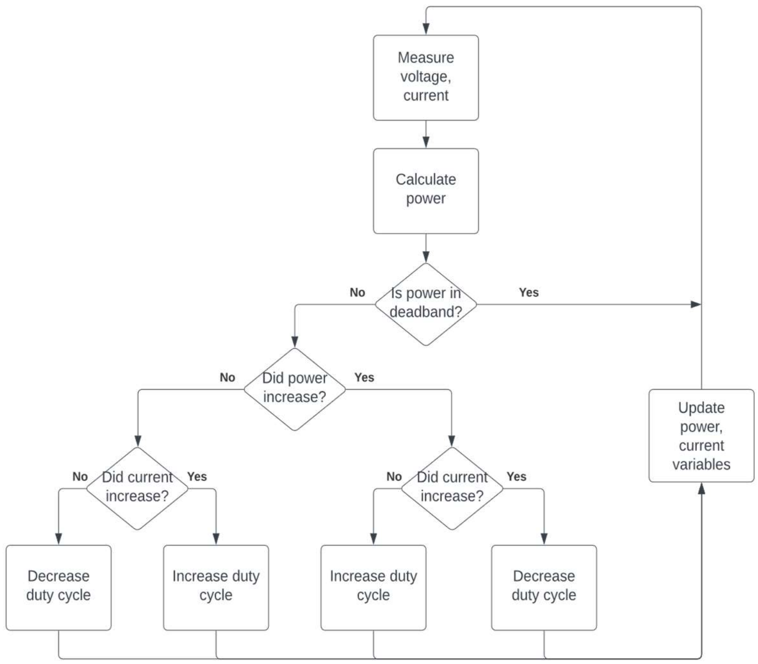

Figure 4: MPPT algorithm flow chart

The code continues to loop until the power settles within an acceptable dead band. This dead band prevents unnecessary adjustments that don't result in significant power changes and provides a condition for the code to break out of the loop.

This code has been continuously tested and adjusted over months. The dead band has been refined to work well with the resolution of the voltage and current sensors. Limits to the duty cycle have been incorporated to prevent extra EMI interference with other components. The basic flow and underlying premise for the algorithm was adapted from a paper found at [5]. This just helped reinforce the necessary flow of the algorithm and ensure that the logic was sound. It also helped that the paper confirmed that their MPPT algorithm was successful, so comparing flow charts was a great sanity check.

Charge controller

This project utilizes two 12 volt 12 Amp-hour sealed lead-acid batteries to power the loads and microcontrollers. These batteries have three different charging stages, as shown in Figure 5. To preserve the health and safety of the batteries, this model has been followed. The SOC of the batteries determines their charging state: constant current, constant voltage, and trickle charge. These correspond to low, middle, and high SOC values respectively.

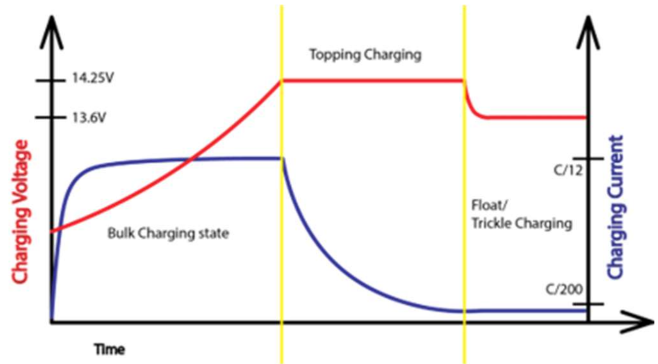

Figure 5: Charging states of the batteries

The SOC code uses Coulomb counting to monitor the states of both batteries and determines when a switch needs to be made.

For the charge controller algorithm, there are three distinct yet similar flow diagrams for the code, shown in Figure 6. There is a loop in the code for each state, which, like the MPPT algorithm, breaks out once the desired output is within the acceptable dead band. Two monitor and adjust current flow from the solar panel, preventing overflow into the battery that will cause damage. The constant voltage maintains 12 volts across the battery at whatever current is required.

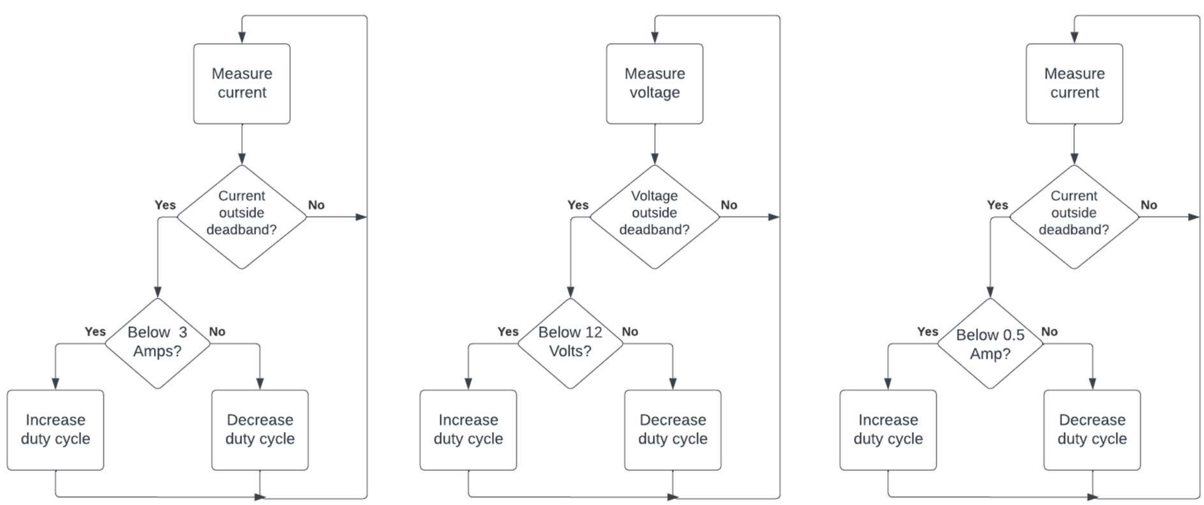

Figure 6: Charge controller flow chart for constant current, constant voltage, and trickle, respectively

This algorithm has been tested thoroughly. Each individual loop has been tested with current and voltage values, and the switching between states has been verified as well. The values are set to parameters best for the battery at each stage to ensure battery health. Once again, there are duty cycle limits that have been set to prevent EMI interference and dead bands to enable the loops to break out to run other code.

5V output

The 5-volt output runs on a similar algorithm to that of the constant voltage stage of the charge controller. The microcontroller gathers the sensor data and either increases or decreases the duty cycle on the switch to adjust the output, as demonstrated in the flow chart in Figure 7.

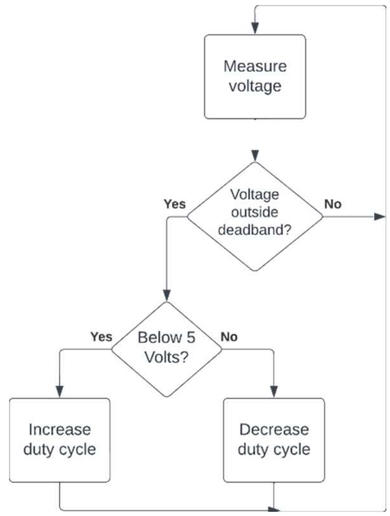

Figure 7: Flow chart for 5-volt output code

This algorithm only runs under two conditions: when the primary battery has a high enough SOC to maintain the load and the user has selected the 5-volt output with the mechanical switch. This is to preserve the health of the battery by not allowing current draw to the loads when it's at a low SOC. The selection of the channel is for user safety and to prevent power losses by running the buck converter unnecessarily.

24V output

The algorithm for the 24-volt output is essentially the same as that for the 5-volt output, as proven with the flowchart in Figure 8. The function is essentially the same: increase or decrease the duty cycle to the switch in response to the voltage on the output.

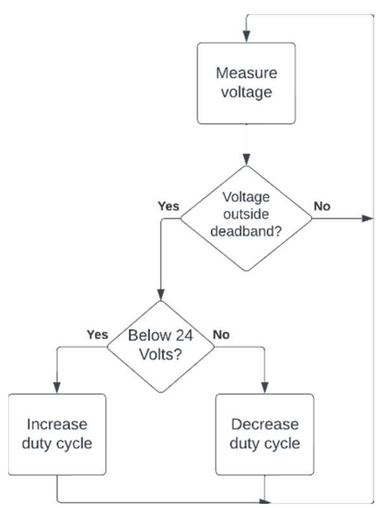

Figure 8: Flow chart for 24-volt output code

Due to the construction of the boost circuit, the duty cycle direction change is the same; other configurations would require the duty cycle directions to flip. This was tested to verify that the duty cycle direction was correct. The duty cycle limitations here are stricter, since just a 40% duty cycle can boost the voltage to 40 volts as was discovered in testing. This is for user safety and protection of the components.

System States

There are three distinct states that the overall system can exist in: primary charge, discharge, and secondary charge mode. These modes determine where current flows throughout the circuit, protecting various components through switches. Digital signals from the microcontrollers control whether the switches are open or closed.

Primary charge mode occurs when the SOC of the primary battery is low, and the secondary battery is still capable of powering the microcontrollers. Connection to the loads is cut off to ensure that no current flow from the solar panel goes to the load. For charging purposes, all this current should go to the battery when it is in the constant current range which is the case in primary charge mode.

Once the primary battery has sufficient charge, the system shifts to discharge mode. In discharge mode, the secondary battery is still capable of powering the microcontrollers and the primary battery has sufficient charge to power the loads. If there are no loads, the primary battery will receive the full amount of current from the solar panel. With loads, the current will branch between the battery and the loads. When in trickle charge state, the current threshold will adjust to accommodate the extra current flow to the loads.

Secondary charge mode is entered once the secondary battery reaches a low SOC. The loads are disconnected and the output of the charge controller is directed to the secondary battery. Charging this battery is a priority, so all current is directed to the battery and all other options are opened. The system will remain in secondary charge mode until the battery is fully charged, since it powers the microcontrollers and gate drivers.

Display

An important part of the project are the LCD displays. The displays are powered by microcontrollers and receive information to display. This information includes the state of the system and the SOC of each battery on one screen. On the other, the most recent current, voltage, and power output of the solar panel is displayed. If there is a load that has been selected by the user flipping a switch, the same voltage, current and power information is displayed for the selected output circuit. If no load is selected, this is displayed for user information as well. All this information is gathered from the saved variables throughout the code.

Another important aspect of the display is that it conveys any error information to the user. When the user needs to flip the manual switch between batteries to change which one is being charged, this will display on the LCD. The system changes state until the correct battery is connected, then continues in the code. Presently for other system errors there is a blanket message that notifies the user that something is wrong. Given more time personalized messages for each type of error could easily be constructed, but the time limitations resulted in a generic message. This notifies the user that an issue has arisen, either in code or hardware, and shuts the hardware components of the system down.

Budget

One of the design constraints that was kept in mind throughout the course of the project was the budget. The goal was to create an affordable and useful small-scale solar power supply, which was accomplished. Overall, the entire project cost under $300 in parts, but this doesn't include labor costs. A breakdown of the costs of items used is shown in Table 1.

Table 1: System Components and their Costs

Component	Quantity	Total Cost (USD)
Renogy RNG-50D-SS	1	49.99
Arduino Leonardo	2	43.98
CB12120 Sealed Lead Acid Battery	2	77.98
Solar adaptor cables (Panel to SAE)	1	11.89
Solar adaptor cables (SAE to alligator)	1	14.96
Infineon IRFZ44NPBF 55V 49A MOSFET	14	18.62
5A breakers	2	3.99
IRS2104PbF Gate Drivers	4	16.68
Heat sinks	14	8.43
20x4 LCD	1	12.89
16x2 LCD	1	9.99
Current sensors	5	11.99
Total Cost		**281.39**

These prices are for normal consumer use, not ordered in bulk for production purposes. There are likely cheaper options for many of the components that can be substituted to decrease the cost, but these were not explored much. For large-scale production, the cost of building each system will likely be well below $1,000, providing an affordable option for utilizing solar energy for consumers. This cost analysis also doesn't include the costs of the capacitors and inductors used, since those were acquired from the supplies available at no cost for the project.

Conclusion

The potential impact of this small-scale battery-based solar power source can be huge. It's a low-power, compact, and affordable system that is easy to use and allows for renewable energy usage in any space. The three different output levels allow for the charging and powering of many different devices, and the LCD enables the user to monitor the system and power usage of their devices. Many different safety aspects have been built in to guarantee both user and component safety in the long run.

One of the most important aspects of the system is the microcontrollers and the code running on them. This allows the system to operate in different states, and lets the outputs at each stage to be stable due to the feedback built in. External interference can be accounted for and corrected in code to guarantee smooth outputs for the MPPT, charge controller, and output algorithms. SOC information is utilized to set system states, and LCDs display system information and any error or warning messages.

This project has taken months to complete but was within an achievable scope. It was a group effort, with each member focusing on a different aspect of the project. There was plenty of testing and revisions of the circuits and code, but confidence can now be placed in the project that it functions as expected. Given more time, there are plenty of other features that can be added to the design, such as more informative error messages and better components for increased efficiency, but given the time and budget constraints this was a very successful endeavor.

References

[1] D. Desilver, "As national eviction ban expires, a look at who rents and who owns in the U.S.," *Pew Research Center*, Aug. 02, 2021. https://www.pewresearch.org/fact-tank/2021/08/02/as-national-eviction-ban-expires-a-look-at-who-rents-and-who-owns-in-the-u-s/ (accessed Nov. 09, 2022).
[2] R. Brill and Pelchen, Rebecca, "How Much Do Solar Panels Cost?," *Forbes Home*, Nov. 03, 2022. https://www.forbes.com/home-improvement/solar/cost-of-solar-panels/ (accessed Nov. 09, 2022).
[3] Kathryn Parkman, "How Much Do Solar Panels Cost? (2022) | ConsumerAffairs," *Consumer Affairs*, Apr. 28, 2022. https://www.consumeraffairs.com/solar-energy/how-much-do-solar-panels-cost.html (accessed Nov. 09, 2022).
[4] J. Semega and Kollar, Mellisa, "Income in the United States: 2021," *United States Census Bureau*, Sep. 13, 2022. https://www.census.gov/library/publications/2022/demo/p60-276.html (accessed Nov. 09, 2022).
[5] B. Abdelilah et al. "Implementation of Maximum Power Point Tracking (MPPT) Solar Charge Controller using Arduino." *IOP Conference Series: Materials Science and Engineering 353,* 2019. https://iopscience.iop.org/article/10.1088/1757-899X/353/1/012024/pdf#:~:text=The%20MPPT%20(Maximum%20Power%20Point,that%20MPP%20will%20be%20reached