Off Grid Optimized Solar Charging with Several Output Voltage Potentials

ECE 445: Design Document

Team 7
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1. Introduction

1.1 Problem

Due to the effects of climate change, the risk of natural disasters threatens several of the heavily populated areas. In the event of electricity going out for several days during a natural disaster, people are left with no way to charge their phones, flashlight batteries, or any other tools they may desperately need. A device that provides an off-grid energy source with several different output voltage values could be critical for their survival in an emergency. There is further a need for such a device for consumers who want to utilize renewable energy to reduce their carbon footprint, but cannot control how their local electricity is generated or cannot install solar panels due to the cost. Both of these problems demonstrate a need for an off grid energy source, that can be used freely by the user, and is versatile by charging different types of batteries.

1.2 Solution

Our team proposes a solar panel integrated with a cascaded DC-DC Converter, that can provide power to USB and rechargeable batteries in the event of emergencies. The device would utilize off-grid renewable energy and provide charging capabilities to multiple output ports with different power ratings, for example, AA batteries and USB protocol for smartphones. The input power will be sourced from a maximum power point tracking (MPPT) algorithm, and the product will be able to measure and display the total energy accrued from the solar panel. The device can be used year-round to provide renewable energy to homes or to be used in case of an emergency. The device must provide reliable, safe, and reproducible circuitry to allow maximum power to be extracted from the input solar panel, while strictly regulating the power of several output terminals.

The overall product will display the cumulative power received from the solar panel, such that the environmental impact of the device can be measured. Typical applications for this kind of product would include setting this device up to run in remote locations that are isolated from the grid, such as hiking, camping, or in the event of a blackout. The success of the device is based on the amount of energy received from the solar panels, and the necessary regulation of the output potentials.

1.3 Visual Aid

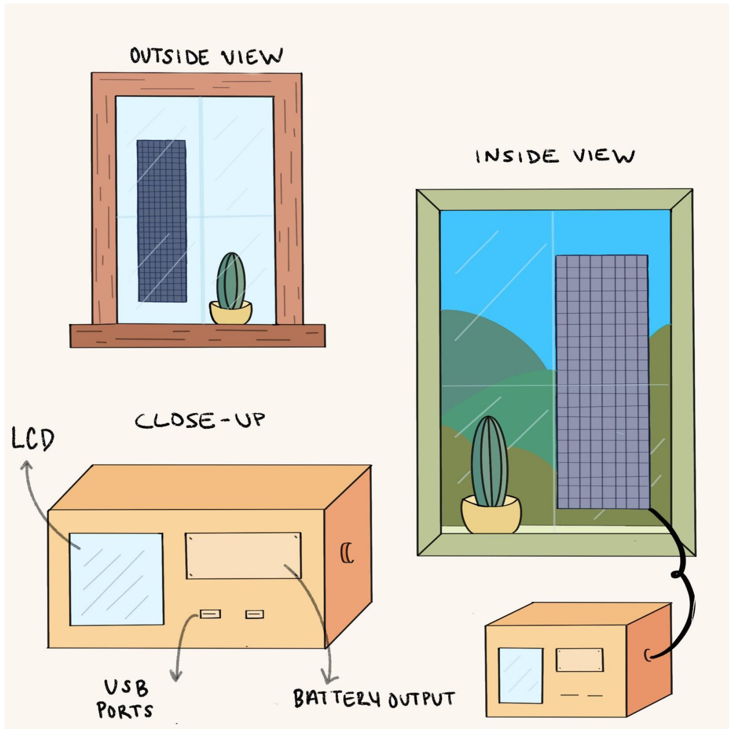

Figure 1: High Level Design

1.4 High-level requirements List

1.4.1 Display energy savings

- MPPT extracts the maximum amount of power over a wide range of ambient weather conditions to maximize the energy savings.
- Display the total energy harvested in kW for the user to provide immediate feedback on the return of investments.

1.4.2 Ability to Work off Grid

- The device must interface the MPPT algorithm with voltage regulators, such that the internal ICs and the microcontroller use the energy harnessed from the solar panel. [1]
- MCU produces all of the internal data signals to process the information, such as sensor feedback data, duty cycle and communication protocols.

1.4.3 Quality of the Output Voltage and Current

- The end product is able to limit the output power to acceptable values (i.e. 10W via USB and 700mAh per battery cells), while still extracting the maximum power from the solar panel according to the MPPT algorithm.
- The battery management system must control the input and the output at the same time.
  - USB charging to be rated at 5V/2A (with ringing and switching) tolerances limited to 2% both on the voltage and current sides.

2. Design

2.1 Block Diagram

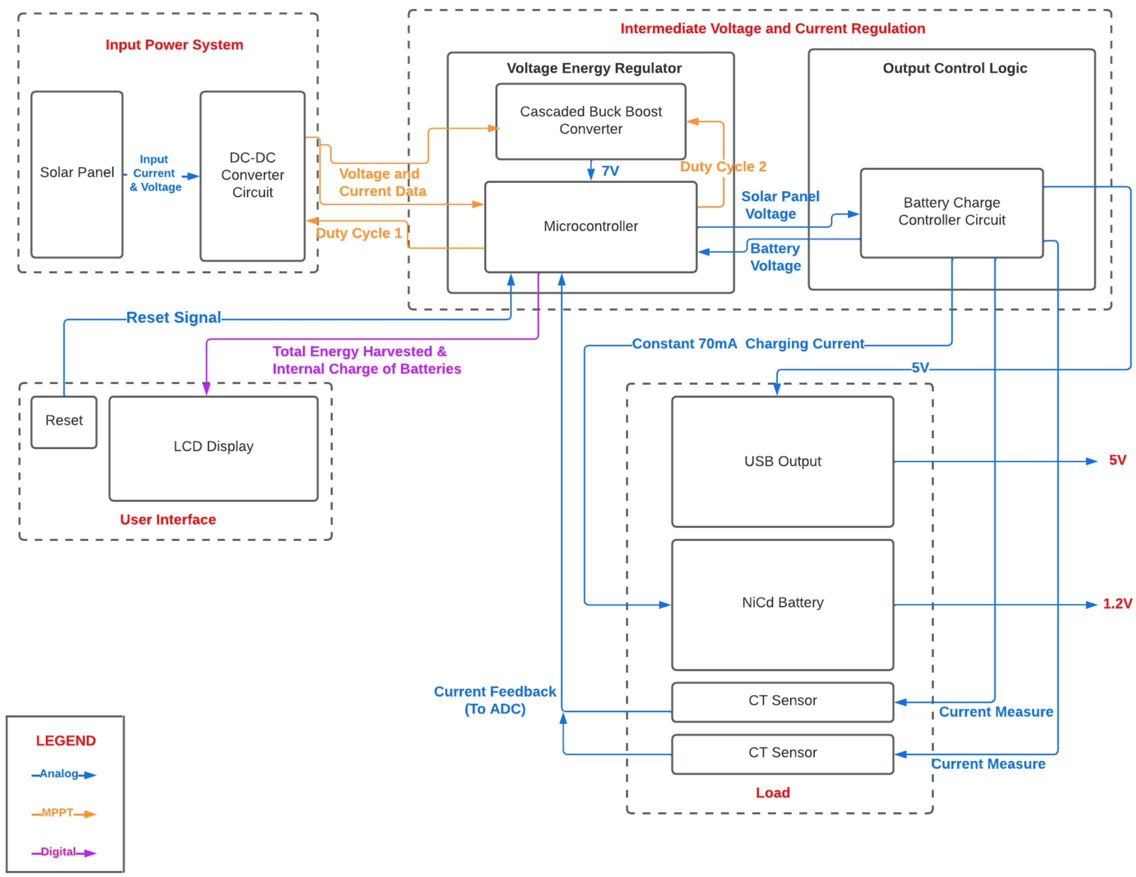

Figure 2: Block Diagram

2.2.1 Input Power System

The input power system itself is implemented by a two stage converter that is connected to the PV cell of our choice. This DC-DC converter is designed based on the available solar panel in the lab, which has a maximum power rating $P_{max} = 100\ W$. Using the conservation of power, $P_{in} = P_{out}$, we expect the output largest power to be a constant 10 W for USB charging. If we account for non-idealities in the design, we will need a minimum of 16 W to power the device, 6 W for the internal circuitry and 10 W for USB I2C charging protocol. Hence the solar panel is more than capable of powering our system. In order to transfer power out of the solar panel, the synchronous buck converter will change the duty cycle applied to the switches to adjust toward the MPP. The output voltage and output current of a buck converter is represented by an equation that is dependent upon the duty cycle of the switching nodes

$$V_{out} = DV_{pv}, D \in [0, 1] \text{ (Eq 1).}$$

Equation 1 is a linear relationship dependent upon D, which is highly desirable for MPPT Proportional-Integrator (PI) control algorithms. Equation 1 is only valid if the buck converter remains in continuous conduction mode, where it must be ensured that the inductor current is strictly positive for the entirety of operation [2]. The buck DC-DC converter will act as the plant, and a current sensor will be connected to the MCU to allow the duty cycle to converge to the maximum power point using a modified incremental conductance algorithm, to ensure the maximum power point is reached [3].

The second stage of the input power subsystem is a specialized DC-DC converter that acts as a voltage regulator to provide 5 V to power internal components. The DC-DC converter consists of a buck-boost converter that is cascaded with the output of the synchronous buck converter. A secondary control loop will utilize the ATMEGA328P microcontroller unit to maintain a constant output voltage of 5 V such that the device can power the internal circuitry - despite the input power changing over time.

In terms of the solar panel unit that is available to us in the ECEB senior design laboratory, there are the following characteristics: P_{max} = 100 W, V_{oc} = 22.4, I_{sc} = 5.92 A
STC: irradiance 200 W/m^2, T = 25 °C, and Am = 1.5. One significant aspect of our design is the lack of curtailment of the solar energy, or inability to reroute power to a larger storage unit. As a team, we decided that the design of a switch mode power supply would be too great of a challenge, given the scope and timeframe of our project. Instead, we have chosen to design this device using two PCBS, a control board for regulating the output power and a power board to extract the maximum input power. This choice lowers the efficiency and return of investments of our design, because the solar panel will be inactive during no load conditions; however our modular design will allow us to incorporate this section in future revisions.

Table 1: R&V for Input Power System

Requirement	Verification
1. Solar power can harvest a minimum of 16 W power on the weather condition in the case of high irradiation.	1. Calculate power harvested with the current and voltage data being collected via MCU and see if the power requirement is being met. a. Does the MCU calculations match using the oscilloscope probe? b. Measure input power and output power, then calculate losses from parasitic elements (MOSFET, switch, diode, ESR, ESL etc.).
2. Ensure that the MPP matches with the theoretical formula: a. $V_{MPP} = k_v V_{oc}$ for $0 < k_v < 1$ b. $I_{MPP} = k_i I_{sc}$ for $0 < k_i < 1$	1. Use an oscilloscope and current sensor to probe the solar panel voltage, and ensure the MPPT algorithm converges to a steady state value. 2. Probe the duty cycle with an oscilloscope and make sure it is not oscillating by more than 5%.

We expect to utilize the buck-boost converter to regulate the voltage required for the MCU and internal IC's. In addition to this topology, we also plan to use a buck or boost converter to model a variable resistor that is dependent upon the duty cycle that we feed into the buck boost converter. This variable resistor model is essentially created because we model R = V/I where V and I are the buck converter's output voltage and current respectively, and this variable resistance is vital to the MPPT hardware implementation.

Based upon our simulations in Figure 3, it is not possible to utilize a buck-boost converter as the MPPT does not allow us to have linear properties with the variable resistor that we have created. As a result, it is advisable to use a buck converter to model our MPPT while then using a buck-boost converter to step up our voltage to the desired 5V/2A. The output waveforms are shown in figure 4, the red line is the current drawn while the green line is the voltage drawn. In order to implement this buck and buck-boost system, two duty cycles are needed to power both the first and second converter. To reduce our ringing with these waveforms, part selection, inverter design, and different properties of parts should be considered depending upon the availability of said parts.

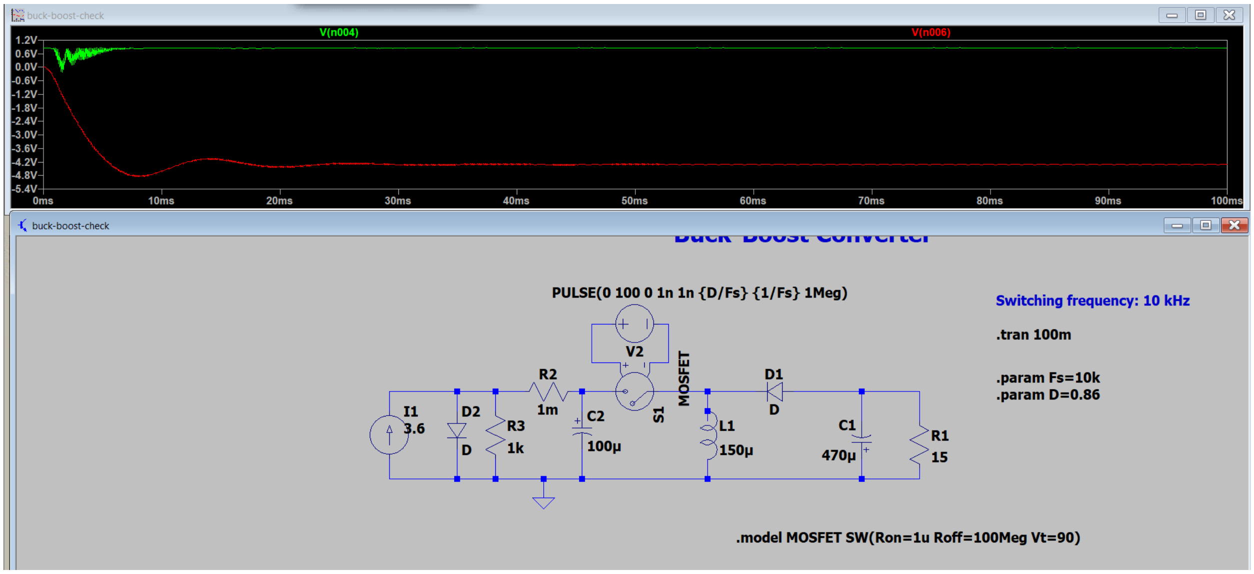

Figure 3: Buck Boost Simulation

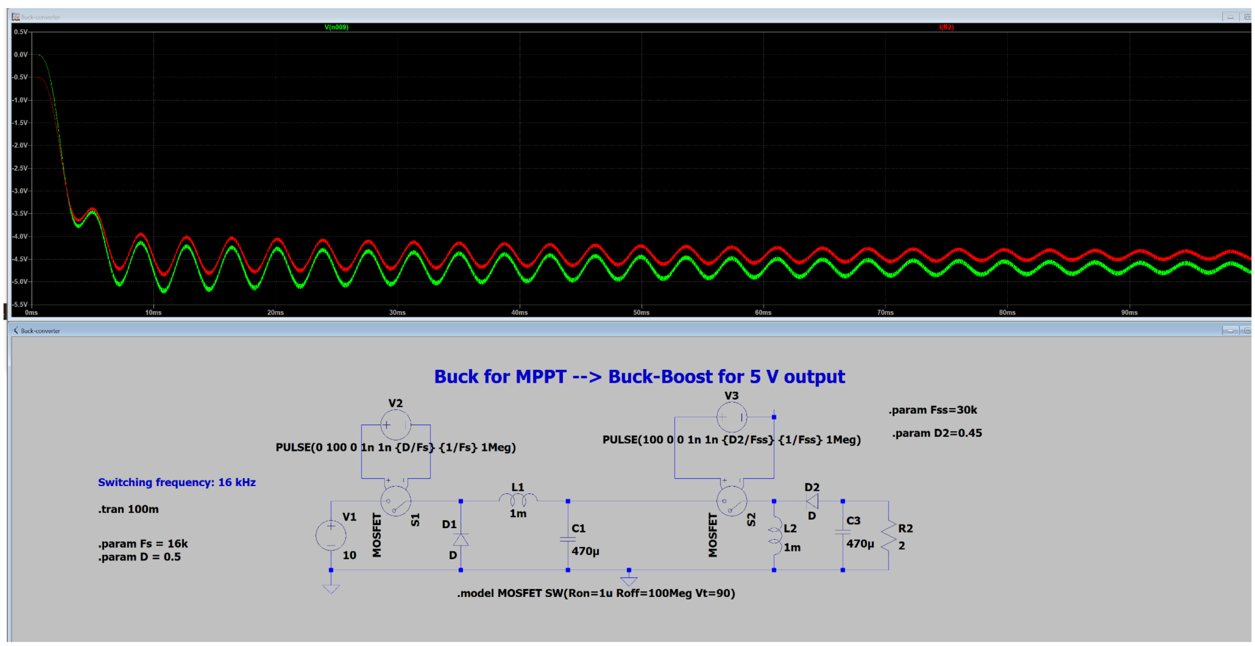

Figure 4: Buck MPPT + Buck-Boost Simulation

2.2.2 Voltage and Current Regulation

- MCU
    - We will use a custom designed microcontroller board to perform MPPT for the solar panels and regulate the solar panel output current . For the microcontroller chip, ATMEGA328P was chosen for its compactness and processing power to handle all of our system controls (i.e. MPPT, Battery management and display control). MCU is capable of being powered two ways: external USB connection

or internal 5V voltage supply rail. This logic was implemented by using comparator logic that is commonly used in the Arduino family of the devices [5].

- PWM pins of the ATMEGA328P were reserved for the MPPT control and battery control. Sensor feedback will be handled using MEGA's on-chip ADCs. Finally, we are planning to use the I2C interface to control the display contents.

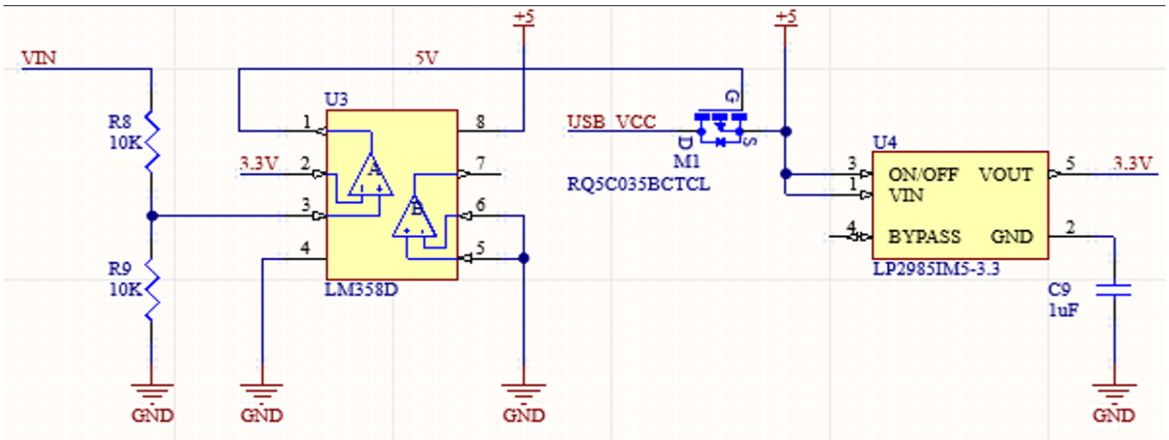

Figure 5: Comparator Circuit for USB vs Internal Voltage Powering

Table 2: R&V for MCU

Requirement	Verification
MCU is correctly being powered via VIN (internal source) and also can be debugged or programmed when the USB is plugged in. 1. Input USB devices should not power the board (FET needs to stay tripped off) when both VIN and USB are plugged in. 2. Regardless of the powering condition, USB data communication should not be interrupted.	1. On the 5 V supply pin of the MCU, 5 V is consistently and reliably being monitored by the multimeter. 2. Switching FET gate side behavior can be monitored using a multimeter to see whether it is turned off when the VIN pin is active. 3. Uploading code to MCU should work all the time regardless of the power sources being used.
1. Based on the current measures coming from the Solar Panel, MCU outputs the correct adjustable duty cycle between 18% to 85% cycle depending on the solar irradiation.	1. Depending on the solar irradiation, duty cycle output changes and correct voltage and current can be monitored via Oscilloscope. 2. Duty cycle output does not exceed the Buck-Boost IC input requirements while it is being monitored by the oscilloscope.

- Cascaded Buck-Boost Converter for Internal Power Delivery
    - After doing further research into the USB charging procedure, we have decided to implement a buck-boost converter instead of a forward converter with a 3-winding transformer [4]. The forward converter is advantageous because it incorporates a three winding transformer to control two different output potentials within a single DC-DC converter, however, each output potential ca. Furthermore, there are no three winding transformers available for purchase that are compatible with our output due to the turn ratios affecting the magnitude of the output voltage. Instead of designing our own transformer and introducing more non-idealities into the system, we designed a buck-boost converter that uses a control loop to regulate the voltage to 5 V, in order to power the battery management system and IC's. This 5 V source will be directly fed into an LDO that regulates USB charging protocol, but also can be supplied directly to the battery management system due to the supported input range of 4 V to 30 V. The main goal of this subsystem is to regulate a constant 5 V power signal from the MPPT algorithm, that can be used to power the internal circuitry and the device can be used isolated from the grid.

Table 3: R&V for Cascaded Buck Boost Converter

Requirement	Verification
1. Intermediate voltages are between 5-7 V as input to the LDO.	1. Measure the output of the cascaded DC-DC converter to ensure the voltage stays within this range.
2. Output currents provide 2 A +/- 2% when charging.	1. Phone or device responds to the actual charging mechanism and also verifies using current probes. 2. Oscilloscope probes show 2 A average signal, using cursors to measure peak ripple.
3. Safety Regulations for output polarity.	1. Ensure the duty cycle is set to 0 when a battery is connected in the wrong polarity (Vout = 0, Iout=0).
4. No load conditions - If a battery is not connected, ensure Iout=0 and all power is rerouted to the energy storage element.	1. Connect Current probe to terminals and measure Iout. 2. Measure the charge flowing into the battery and the change in voltage.

- Battery Charge Controller Circuit
    - To store excess energy after the main energy is drawn from the USB port, nickel cadmium batteries will be used. For the safety and proper charging operation of these batteries, LM317 PMIC will be used to regulate the charging current. NiCd batteries need to be charged with a fixed current, therefore we selected 70 mA which is 10% of the rated capacity (700 mA). The LM317 is configured to operate in a fixed current regulator where it outputs 70 mA according to our NiCd battery specification [7]. The batteries will be connected in series, as a result this charging method is a modular solution. What is meant by a modular solution is that multiple batteries can be charged at a consistent rate as long as the LM317 voltage input can support following condition:

Battery Voltages + Diode Voltage + 40V ≥ VIN ≥ Battery Voltages + Diode Voltage + 3V [8]

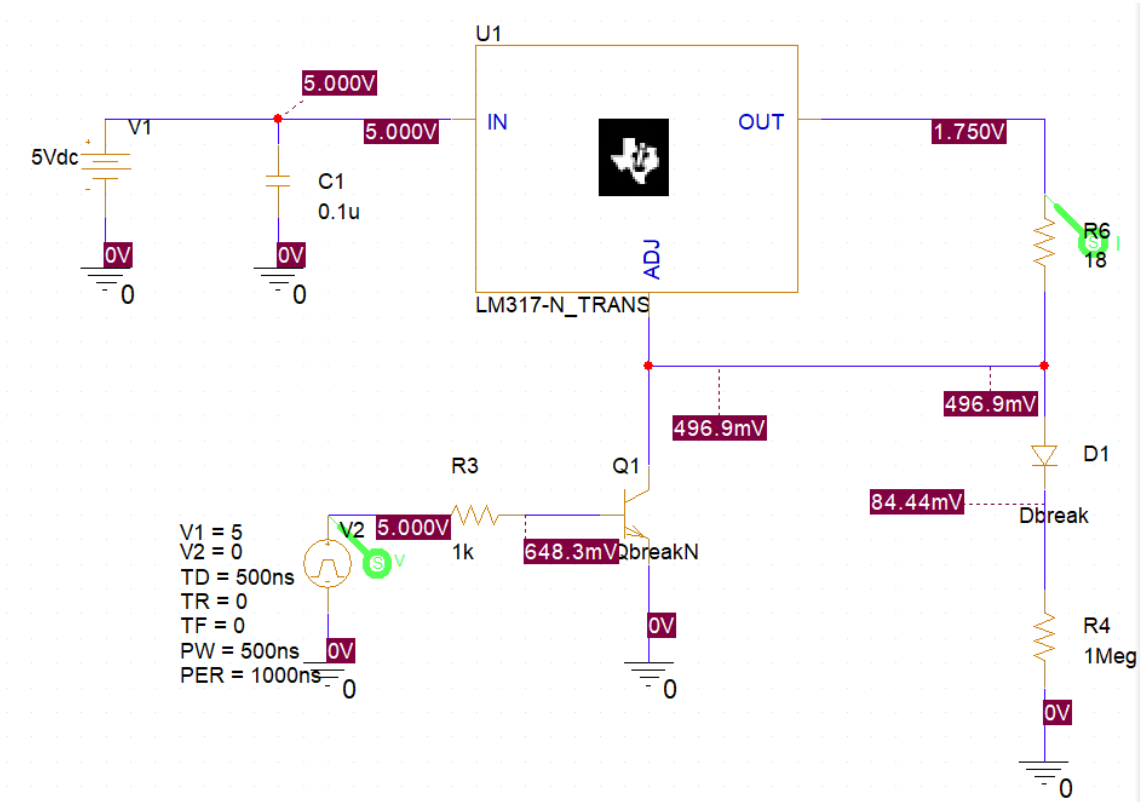

Figure 6: Battery Charging Circuit Simulation Schematic

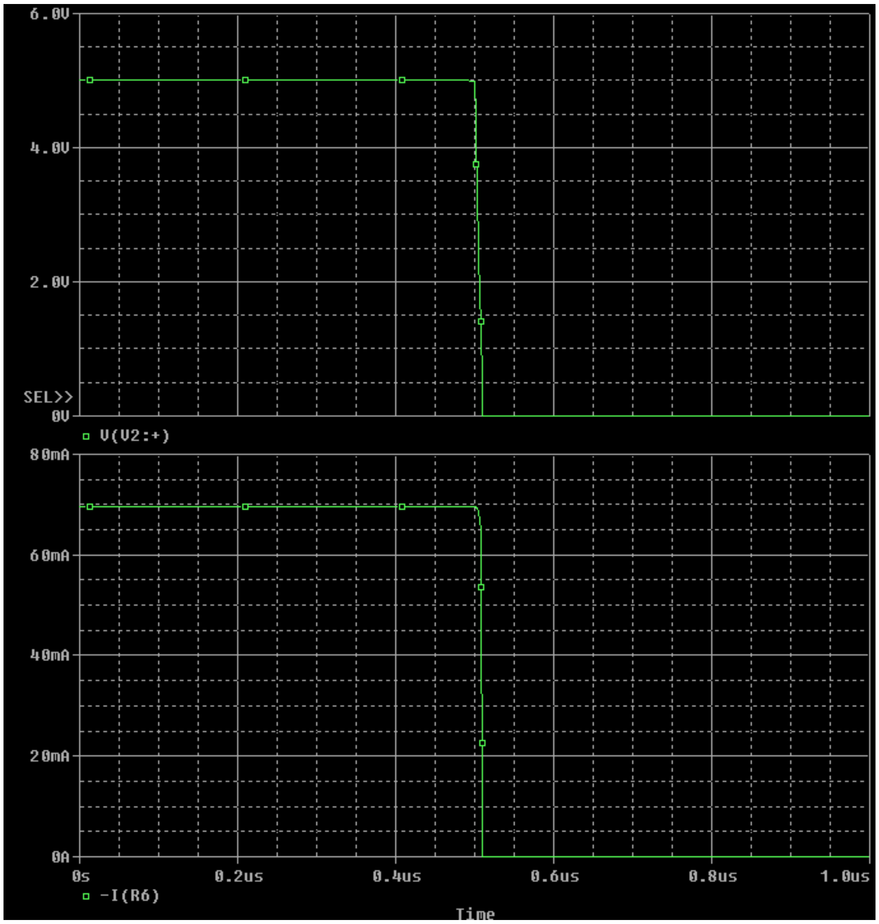

Figure 7: Battery Charging Circuit Simulation Waveform

Table 4: R&V for Battery Charge Controller Circuit

Requirement	Verification
1. Battery (or batteries) is (are) being charged stably under constant current at 70mA (Charging Current = Capacity * 0.1).	1. LM317 current output should consistently be 70 mA within 10% tolerance when measured with a multimeter. 2. As long as VIN = Load voltages + 3V condition is met, constant 70 mA should be measured at the output of LM317 when measured with a multimeter.
2. According to the battery charge levels, MCU should trip or turn on the battery charging circuit.	1. When the battery level is over 95% (battery voltage of 1.2V) mark, MCU trips the charging circuitry, blocking the current flow to be around mA level when measured with a multimeter. 2. If the battery charge is below 95%, MCU should turn on the charging circuitry to charge

	the batteries at 70mA rate.
3. LM317 operating temperature is below 125°C [8].	1. While charging the battery, monitor LM317 temperature with a thermometer. This also acts as an overall test to see if the designed heatsink is doing an efficient job.
4. Output voltages are at 5 V +/- 2% when charging.	1. Phone or device responds to the actual charging mechanism and is also verified using differential probes. 2. Oscilloscope probes show 5 V average signal, using cursors to measure peak ripple.
5. Output currents provide 2 A +/- 2% when charging.	1. Phone or device responds to the actual charging mechanism and also verifies using current probes. 2. Oscilloscope probes show 2 A average signal, using cursors to measure peak ripple.

2.2.3 User Interface

- LCD Display
    - A simple display will be mounted on the system to show data on our current conditions. The data focuses on displaying total energy harvested and battery charge level. The display itself will show the battery status level, providing useful insight into the current state of the batteries. Since the device is intended for off-grid operation, it is imperative that the device can operate during the low solar irradiation weather. Total energy harvested will be an important indicator of how much energy users can save by using this device. I2C communication is used to transmit data between the LCD and the MCU, because it only requires two I/O pins for the SDA and SCL lines respectively.

Table 5: R&V for LCD Display

Requirement	Verification
I2C communication should be constantly communicating with the MCU and displaying real time data on our energy harvest (W) and battery status (%). 1. Display acts correctly as a slave and correct driven by the behavior set by SDA port of the MCU [6]. 2. Displays correct battery charging percentage in reference to 1.25 V maximum voltage rate and outputs battery percentage to the display in scale of 0 to 100%. 3. Displays total energy being harvested by solar panel in between 0 to 100 W by using MPPT algorithm data (Voltage between 0 V to 22.4 V and current between 0 A to 5.92 A).	1. When the oscilloscope is observing the SCL port during the data exchange: a. At the falling edge, set data bits. b. At the rising edge, capture data bits. 2. Battery charge level can be verified by checking if the displayed percentage is consistent with multimeter probed battery voltage. 3. Displayed wattage is consistent within 2% tolerance with the calculated instantaneous power calculated via oscilloscope.

2.3 Tolerance Analysis

One area of conflict that we must be prepared for, is the possibility that our 5 V regulator produces a significant amount of voltage ripple and current ripple due to the high switching frequency in our circuit. We expect our switching frequency applied to the gate of each mosfet to be between 100 - 500 KHz to minimize switching losses in the DC-DC converters [3]. If the switching noise exceeds our voltage ripple of 2% of 5 V, our cascaded DC-DC converter could exhibit unwanted behavior, due to MPPT conflicting with output voltage regulation. The MPPT algorithm regulates the input voltage and input current of the solar panel, but does not regulate the output voltage due to the dependency on $V_{Intermediate} = D_1 V_{sp}$. The cascaded Buck-Boost converter has a relationship $V_{final} = V_{intermediate}(D_2/1 - D_2)$ where the secondary control algorithm will regulate the final voltage applied to the battery management IC. If there is any mismatch between D_1 and D_2, the two control algorithms may not converge to an exact value and the input to the battery management unit is unstable. One way to fix this is the use of Zener Diodes placed in reverse bias across the terminals V_Final, such that the output voltage is clamped to 5 V regardless of the current. This ensures that the average voltage does not exceed the reverse breakdown of the zener diode, and the design of output filters can further reduce the ripple voltage. Figure 8 demonstrates this through simulation, where a Zener Diode was selected to have $V_{BR} = 4.5\ V$ and the output filter was increased by adding a larger capacitor. By comparing these results to Figure 4, we see that the output voltage is less sinusoidal, and the ripple decreased from 1 V to 500 mV. Unfortunately, this does not meet the requirements outlined in Table 2, due to the lack of input capacitors and the buck converter output capacitor being cascaded into a secondary DC DC converter.

$$C_{O(min)} = \frac{I_o D}{f_{sw}\left(V_{O(PP)} - \left(\frac{I_o}{1\text{-D}} + \frac{I_{L_1,PP}}{2}\right)\right)} \quad \text{(Eq. 1)}$$

$$C_{in} \geq \frac{D(1-D)I_L}{f_{sw}\Delta V_{C_{in}}} \quad \text{(Eq. 2)}$$

These equations are dependent on the duty cycle of each converter which is controlled by the MCU and control feedback mechanisms. As a result, equations 1 and 2 are indicated in terms, D, which is a generic duty cycle that can be applied for both our buck and buck-boost converter. These will allow us to choose our capacitors accordingly and ultimately limit our ripple voltage to allow for a cleaner output voltage level. As the duty cycle changes, we will want to pick the largest capacitance required for a given duty cycle and current draw. These values were approximated in simulation, due to our inability to simulate maximum power extraction in LTSpice.

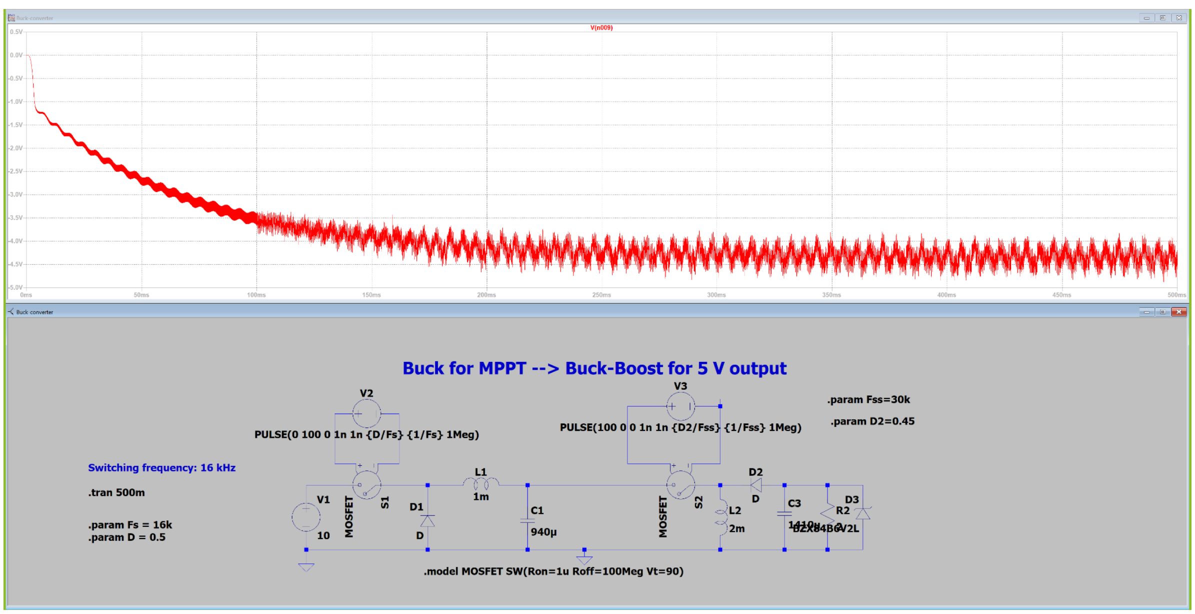

Figure 8: Reduced Ripple at the output using Zener Diode and larger LC ripple.

2.4 Schematic

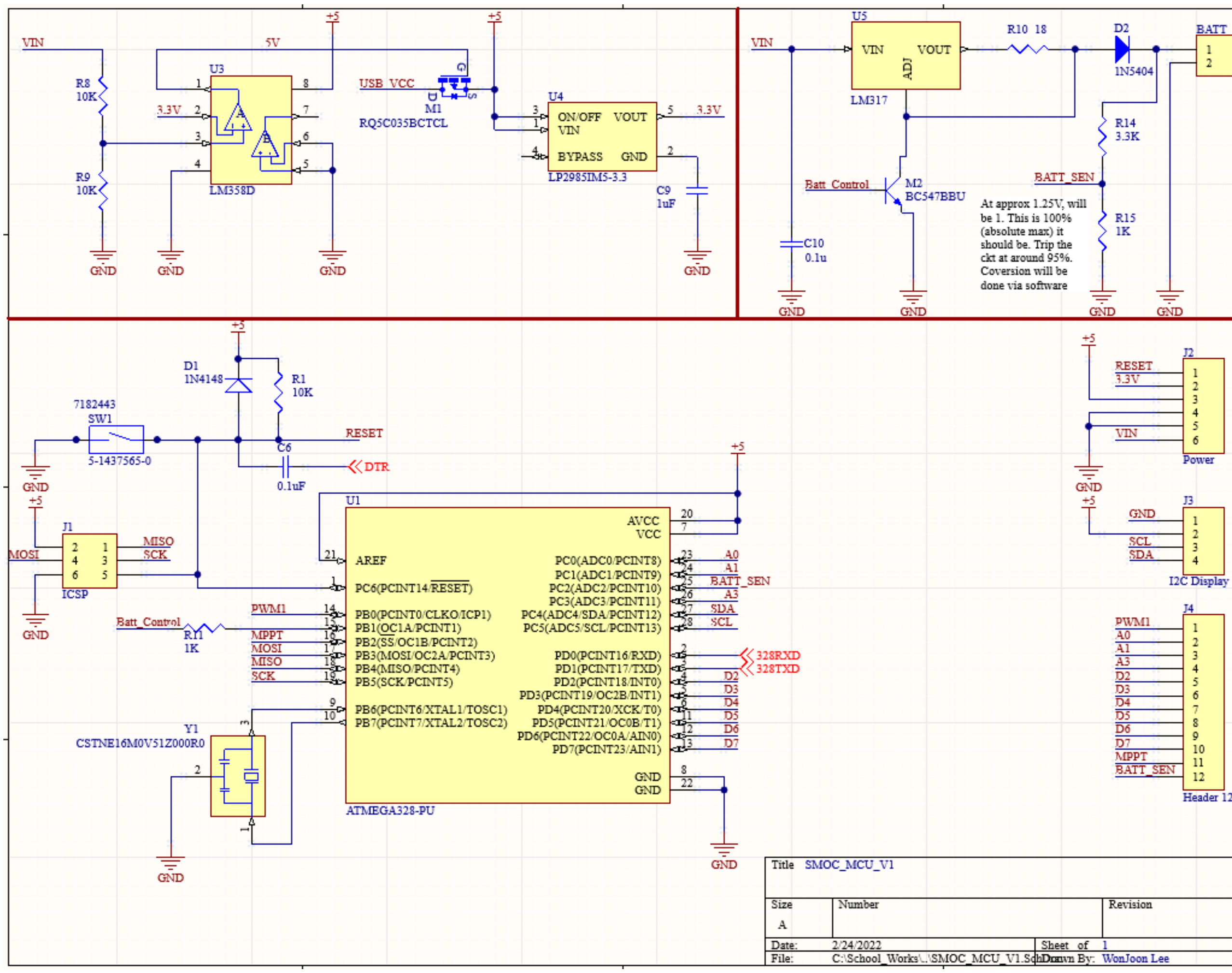

Figure 9: MCU Board Schematic Page 1 (MCU, Display, Power Logic and Battery Charging Circuit)

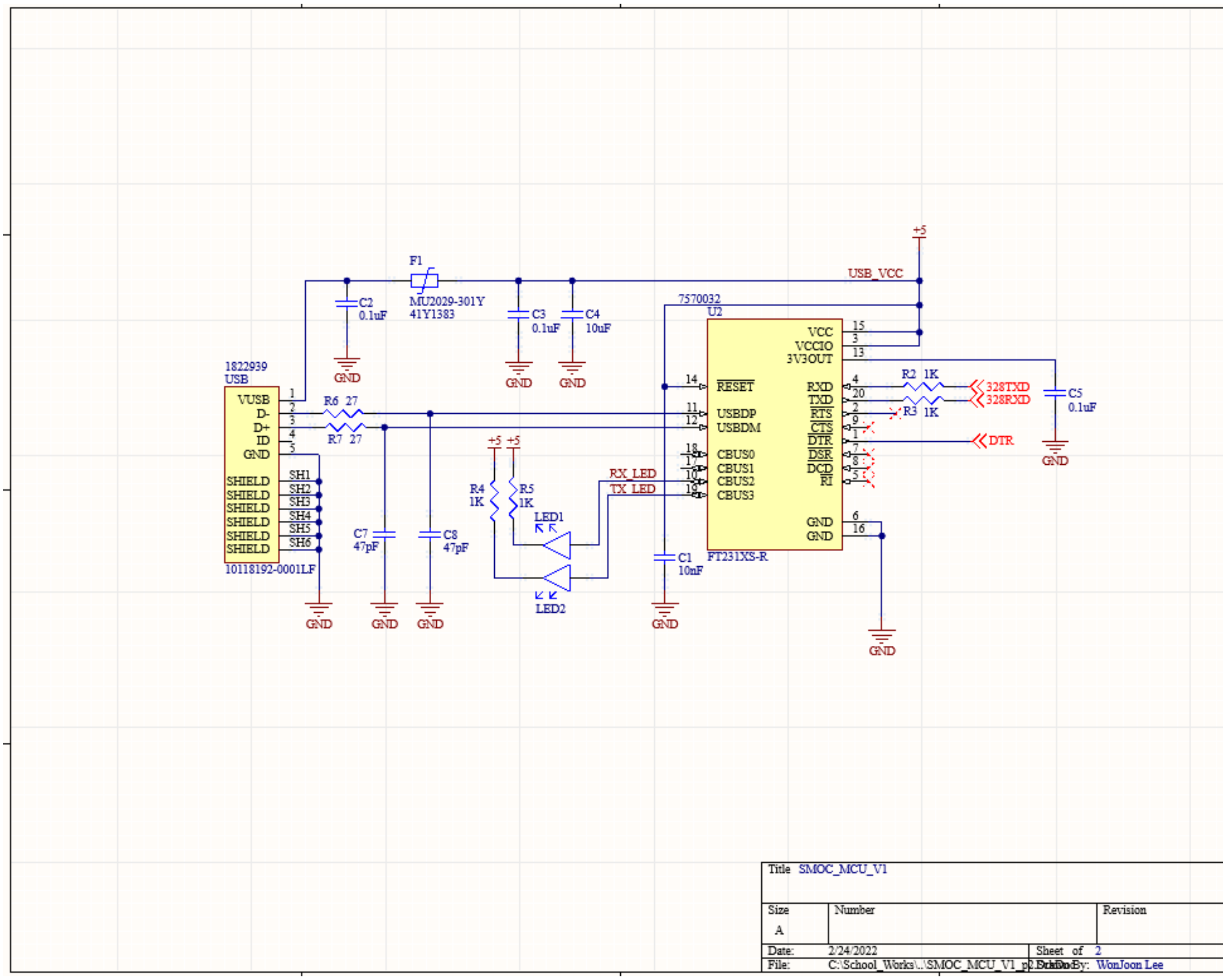

Figure 10: MCU Board Schematic Page 2 (USB Protocol)

3. Costs

3.1 Cost Analysis

Table 6: Labor Costs

Name	Hourly Rate	Hours	Total / Person	Total * 2.5
Lukas Gollings	$30.00	160	$4,800.00	$12,000.00
WonJoon Lee	$30.00	160	$4,800.00	$12,000.00
Kanin Tangchartsiri	$30.00	160	$4,800.00	$12,000.00
Total cost for the team				**$36,000.00**

Table 7: Parts Costs

Part	Manufacturer	Quantity	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
PV Cell (provided by ECE)	n/a	n/a	n/a	n/a	0
CT sensors	Seeed Technology	1	$9.5	$9.5	$9.5
DC DC Converter IC's	Analog Devices	1	$20	$20	$20
ATMega328p	Microchip	1	$5.50	$5.50	$5.50
Ferrite Bead	Bourns	1	$0.02	$0.02	$0.02
LED	Optoelectronics	3	$0.02	$0.06	$0.06

Push Button Switch	TE Connectivity	1	$0.04	$0.04	$0.04
FT231	FTDI	1	$2.59	$2.59	$2.59
USB Connector	Amphenol	1	$0.23	$0.23	$0.23
16MHz Ceramic Resonator	Murata Electronics	1	$0.29	$0.29	0.29
Battery	Panasonic BSG	2	$2.28	$5.60	$5.60
1N4148	Diotec Semiconductors	1	$0.11	$0.11	$0.11
1N5404	Tube Depot	1	$0.35	$0.35	$0.35
I2C Display	Frienda	1	$17.99	$17.99	$17.99
RQ5C035BC TCL	Rohm Semiconductor	1	$0.45	$0.45	$0.45
BC547BBU	Onsemi	1	$0.38	$0.38	$0.38
LM358D	STMicroelectronics	1	$3.09	$3.09	$3.09
LP2985IM5-3 .3	Texas Instruments	1	$1.39	$1.39	$1.39
LM317	Onsemi	1	$0.83	$0.83	$0.83
LTC1149CN	Analog Devices	1	$12.78	$12.78	$12.78

CRG0805F10K	TE Connectivity	3	$0.01	$0.03	$0.03
AC0805FR-101KL	Yageo	6	$0.01	$0.06	$0.06
ESR10EZPJ332	Rohm Semiconductor	1	$0.01	$0.01	$0.01
ESR10EZPJ27R0	Rohm Semiconductor	2	$0.18	$0.36	$0.36
PR01000101809JR500	Vishay	1	$0.03	$0.03	$0.03
CL21B104KBCNNNC	Samsung Electromechanics	4	$0.1	$0.4	$0.4
104MPW160K	Illinois Capacitor	1	$0.54	$0.54	$0.54
C0603C0G1H470J030BA	TDK Corporation	2	$0.1	$0.2	$0.2
C2012X5R1A106K085AB	TDK Corporation	1	$0.28	$0.28	$0.28
08055C121KAT2A	Kyocera AVX	1	$0.25	$0.25	$0.25
Total	**n/a**	**n/a**	**$ 79.19**	**$ 83.17**	**$ 83.17**

Table 8: Grand Total

Category	Cost
Labor	$ 36,000.00
Parts	$ 83.17
Total	**$ 36083.17**

3.2 Schedule

Table 9: Schedule

Week (Mon)	Lukas	WonJoon	Kanin
2/21	- Finish simulations of output battery terminals. - Clarify with instructors how the solar panels are shared. - Finish simulation of solar panel as input.	- Design of MCU and necessary connections. - Begin ordering parts. - Design of analog circuit for battery management.	- Finish part selection and input power control design and simulations. - Solidify implementation with regards to duty cycle control and converter topology.
2/28	- PCB design of core power traces/devices. - Finalize list of parts. - Simulations of cascaded DC-DC converters.	- Design of MCU and necessary connections. - Begin ordering parts. - Design of analog circuit for battery management.	- Part tracking and selection. - Implementation of MPPT Algorithm on the ATMega or other more efficient variations of power tracking algorithms.
3/7	- Ensure all parts are ordered. - MCU programming.	- Begin programming MCU.	- MCU programming.
3/14	Spring Break	Spring Break	Spring Break
3/21	- Begin assembling and testing MPPT Cascaded DC-DC converter as soon as parts arrive.	- Begin Programming the MCU	- Assist with assembly and programming as needed.
3/28	- Benchmark the MPPT Power	- Assemble all MCU components on	- Debugging help and emergency part orders

	Supply - Assist in programming MCU	board	
4/4	- Debugging PCB	- Assembling the Battery Management system and characterizing output terminals	- Help finish assembly of the board and begin characterization and verification.
4/11	- Testing and Verification	- Debug critical issues	- Testing and Verification
4/18 Mock Demo	- Final Debugging plus Organize presentation	- Record final measurements, waveforms, and data for final report	- Record final measurements, waveforms, and data for final report
4/25	- Rehearse demo + work on final report	- Rehearse demo + work on final report	- Rehearse demo + work on final report
5/2	- Practice Presentation and Finish Final Report	- Practice Presentation and Finish Final Report	- Practice Presentation and Finish Final Report

4. Discussion of Safety and Ethics

The IEEE Code of Ethics states that members are hereby committed to "uphold the highest standards of integrity, responsible behavior, and ethical conduct in professional activities" [9]. With this in mind, we have compiled a few risks associated with this project. These risks are especially important since we are utilizing batteries as a power source while also reporting our current power outputs.

In terms of ethics, we want to make sure that we understand the safety and the risks associated with utilizing external batteries. This involves each member of our team conducting the battery safety training that has been provided to us by the course staff here at ECE 445. Precautionary measures that we can take include ensuring that we protect our system from overheating, loss of voltage and other surges that could occur while the device is operating. We will also ensure that the batteries cannot be connected with the wrong polarity through reverse blocking diodes and transistor networks. Furthermore, it is best if we can isolate the power signals and the data signals in our design, such that the PCB manufactured is not at risk of accidental short circuits destroying the device or battery. This is also extremely important for simulations and component selection, where we must ensure each component does not create a fault in the battery management system. These components must be designed and chosen to have the correct power ratings, such that the MPPT algorithm does not damage the component and jeopardize the integrity of the battery. Additionally, wherever possible we must adhere to strict IEEE codes based on electrical charging stations; while ultimately these codes are utilized for vehicle charging stations, the information gathered and safety standards utilized will provide extra tolerances and peace of mind for users and engineers [10].

Furthermore, we will be tracking overall power input into our system, therefore, it is our responsibility as the engineers to make sure that these values are accurate as they may be used to supplement other use cases and as such may be reported as official statistics. Providing accurate and precise information is important to consumers and is also advised under IEEE Code of Ethics under section 7.8 section 1.5 whereby it is stated that individuals must "be honest and realistic in stating claims or estimates based on available data" [11]. This will be apparent in future reports and revisions to our project, where the device provides reliable and accurate data to the user.

Citations

[1] "LM2678 SIMPLE SWITCHER High Efficiency 5-A Step-Down Voltage Regulator datasheet (Rev. K)", *Ti.com*, 2017. [Online]. Available: https://www.ti.com/lit/ds/symlink/lm2678.pdf?HQS=dis-dk-null-digikeymode-dsf-pf-null-wwe&ts=1644524404307. [Accessed: 10- Feb- 2022].

[2] B. Abdi, L. Yazdanparast, H. Gholamrezaei and S.M.M. Mirtalaei, “Reliability Comparison of MPPT Converter in DCM and CCM Operation,” Oct. 2011.

[3] Manel Hlaili, Hfaiedh Mechergui, and Vishal Mehta, Ed., Comparison of Different MPPT Algorithms with a Proposed One Using a Power Estimator for Grid Connected PV Systems. Hindawi, 2016.

[4] "USB Battery Charging Guide | Maxim Integrated", *Maximintegrated.com*. [Online]. Available: https://www.maximintegrated.com/en/design/reference-design-center/ref-circuits/3241.html. [Accessed: 10- Feb- 2022].

[5] Arduino, “Arduino Uno REV3,” Arduino Online Shop. [Online]. Available: https://store-usa.arduino.cc/products/arduino-uno-rev3/. [Accessed: 25-Feb-2022].

[6] Campbell, S., 2022. Basics of the I2C Communication Protocol. [online] Circuit Basics. Available at: <https://www.circuitbasics.com/basics-of-the-i2c-communication-protocol/> [Accessed 25 February 2022].

[7] Electronics-diy.com. 2022. Intelligent NiCd/NiMH Battery Charger. [online] Available at: <http://electronics-diy.com/electronic_schematic.php?id=813> [Accessed 25 February 2022]

[8] www.ti.com. [Online]. Available: https://www.ti.com/lit/ds/symlink/lm317.pdf?ts=1645595845472&ref_url=https%253A%252F%252Fwww.google.com%252F. [Accessed: 25-Feb-2022]..

[9] S. Gupta, "How to design a 5V 2A SMPS Power Supply Circuit", *Circuit Digest*, 2019. [Online]. Available: https://circuitdigest.com/electronic-circuits/5v-2a-smps-power-supply-circuit-diagram. [Accessed: 10- Feb- 2022].

[10] S. G. Tesfahunegn, O. Ulleberg, T. M. Undeland, and P. J. S. Vie, “A simplified battery charge controller for safety and increased utilization in standalone PV applications,” in *2011*

International Conference on Clean Electrical Power (ICCEP), 2011, pp. 137–144.

[11] IEEE Board of Directors. “IEEE Code of Ethics.” IEEE Code of Policies, Section 7 - Professional Activities (Part A - IEEE Policies). [Online]. June 2020. https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed 10- Feb- 2022].