MOBILE MONITORING BOX FOR SOLAR

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Abstract

This report covers Team 7’s WiFi-enabled photovoltaic measurement solution. This device will allow users to easily monitor the output of their solar array, while having complete control over their data. Most of the devices core elements have been tested and proven in expected conditions. The report is organized as a timeline through the purpose, design process, results, analysis, and future plans.

Contents

1. Introduction

1.1 Objective

Photovoltaic systems will play a large role in the future, decarbonized energy sector. Solar installations are projected to continue growing and the cumulative power produced will surpass 100 GW by 2021 [1]. Currently, the inverter systems that these panel arrays rely on are string/central, microinverters, or string with power optimizers. Microinverters and power optimizers make a system more efficient and mitigate the detriments that a lone, poor-performing panel may have on the aggregate performance [2]. Popular microinverters, like those produced by Enphase, internally monitor and transmit data that is made available through their proprietary software [3]. Similarly, the top producer of power optimizers, SolarEdge, features module-level power electronics which monitor metrics that is sent through a built-in ethernet connection to be accessed through their monitoring server [4]. Although these modular options improve the system's efficiency and provide transparency in system failures or weaknesses, these installations involve extra infrastructure, come at a higher initial cost, and the data delivery is managed by the manufacturer's software. Without these devices, problems are experienced at the string level and localizing the issue can be difficult, if not impossible, without taking the string offline. The percentage of systems with the monitoring benefits of module-level power electronics is about 15% for residential and 35% for small non-residential arrays in 2018 [5]. The cost due to loss of energy production that an unmonitored system may face is the main factor in offsetting the extra initial costs for module-level power electronics [6]. If a monitoring system had minimal installation along with cheap and accessible data collection, then string inverter systems may benefit from its lower initial cost without risking energy production.

Our solution is a mobile monitoring device that can send direct measurements back to its user via Wi-Fi. The device centralizes the measurement components, which drives cost down but sacrifices monitoring resolution. The function of the tool essentializes data collection by reading only current and voltage values associated with an individual panel, DC or AC. Having data directly transferred over Wi-Fi avoids excess architecture and allows the user to have greater freedom with data analysis, rather than being bound by the manufacturer's software. Permanent installations would include a simple terminal block at each panel to measure the DC and AC values. Our goal is to lower the costs for a monitoring system by limiting resolution, simplifying the data set, and providing direct access to data analysis.

1.2 High-Level Requirements

- Device must safely monitor voltage and current levels on load and line without significantly affecting performance.
- Device must transfer data packets through WiFi to a local PC
- Device must be durable enough to withstand reasonable outdoor weather conditions

2 Design

There are 4 (5 if you include the terminal box) sections that allow this product to be accurate and easy to use. The power supply section provides the microprocessor with 3.3 V of power in order to run. The terminal box will connect to the photovoltaic system both before the inverter and after the inverter. The terminal box will do nothing to the PV system, but give us easy access to ports that can measure the voltage and current before and after the inverter. The measurement section will connect to the terminal box, and then the voltage values are scaled down by a voltage divider and the current is measured by Hall-effect based sensors. The microcontroller processes the converted input signals to represent the original values. The Particle Photon well then send the processed data over WiFi to the user's PC as cloud variables. The computer will have an interface that allows the user to view all the data collected.

2.1 Power Supply

The power supply is necessary to provide the microcontroller with the needed voltage to work. The power supply consists of a rechargeable battery. The battery's voltage is then regulated by the Photon, to supply other IC's with a 3.3V.

2.1.1 Battery

The battery will be a 3.7V Li-Ion rechargeable battery. The battery will be charged using an external charging circuit. We will be wiring the battery to power the MCU. The specific battery that we will be using the SparkFun Electronics PRT-12895. The battery will have a range of 2.5V - 4.25V depending on

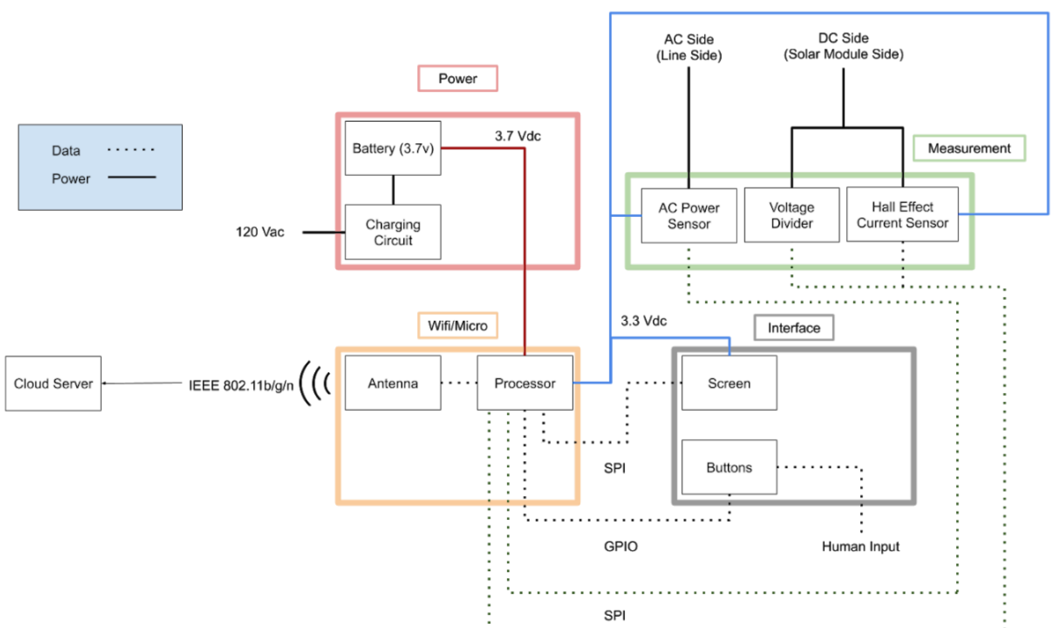

Figure 1: Block Diagram

whether the battery has no charge or at a full charge respectively. The battery has a capacity of 2.6 Ah.

2.1.2 Charging Circuit

The charging circuit was originally engineered to be an external circuit. However, the Particle Photon can charge a battery, so the external charging circuit was removed. The Photon will be powered by the battery, but once power is supplied to the Photon via its micro-USB port, power flow is reversed to charge the battery. The Photon provides the correct voltage, 4.2 V, but it is limited to 1 A of current instead of the optimal 1.2 A needed for charging. This isn't a problem as it just extends the charging time from 4 hr. to 5.2 hr.

2.2 Measurement

The measurement section interacts with the terminal box to collect the actual voltage and current from the photovoltaic system.

2.2.1 Terminal Box

The terminal box will provide access to the voltages and currents of the module while under load. It will be permanently installed on the panel at minimal cost in comparison to installing full measurement solutions. This allows measurement of the system without losing the power it generates and adds convenience for users.

While AC voltage/current and DC current measurement is possible through magnetic field interactions, out of circuit DC voltage measurement is currently developing and a delicate technology. The terminal box is a simple and rugged solution to this issue.

Our device leads will match those of the PV panels located on the ECEB building, so if users do not wish to use the terminal box, they can disconnect their system to measure DC voltage.

2.2.2 AC Power Monitoring (AC Sensing)

The power monitoring will measure the voltage and current amplitudes on the line side of the inverter. The AC sensing will be managed by Allegro's ACS71020 IC. This device has Hall-effect based current sensing and an input range of 0-30A. The voltage sensing occurs at a range of 275mV, a voltage divider circuit of four 1MOhm resistors scale the incoming line voltage across a calibrated sense resistor. At an expected RMS value of 120V, a low tolerance sense resistor of 4.7kOhm will be chosen. The peak voltage at the IC's input will then be rated at 199mV. Each of the 1MOhm resistors will dissipate a rated 0.9mW, which combined consumes far less than 1% of the panel's rated 425W generation.

The input signals are then converted to digital signals, that will communicate via an SPI protocol. The voltage levels of this digital signal may need further step down, which will be covered by another voltage divider. This reduced value is then sent to a protection circuit before it is sent to the microcontroller.

The current and voltage sensing is affected by temperature, but the IC includes an internal temperature sensor. The temperature readings then provide an input to the compensation logic.

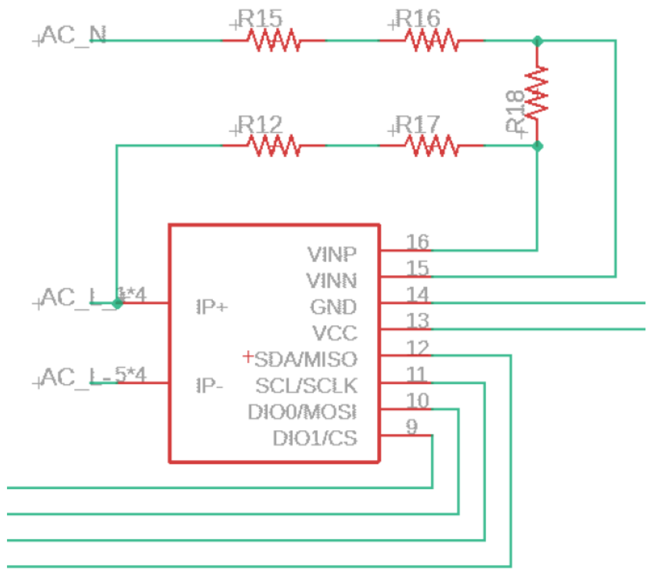

Figure 2: AC Sensing Schematic

2.2.3 DC Sensing Voltage Divider

When measuring the DC side of the Solar Module, the voltage will be dropped to a voltage significantly less than 1v. The rated operating voltage of the panel is 72.9V. As a preliminary calculation, a sense resistor of 33KOhm in series with 4 1MOhm resistors would scale the rated voltage to .597V and the rated open-circuit voltage to .7V. The power dissipation across the 1MOhm resistors will be about a third of a mW, which is much smaller than rated 425W of the panel. The resulting analog voltage is then sent to the microcontroller to be processed.

2.2.4 Hall-effect Based DC Current Sensor

A DC current sensor will be used to measure the panels output current and deliver that data to the microprocessor. The intended sensor will be Allegro's ACS722 series. This IC series is an Open Loop, Hall Effect-based current sensor. The rated operating current of the panel is 5.83A and the short circuit rating is 6.18A, so an input of up to 10A will be chosen. The primary conductor resistance for the input current is about 0.65mOhm, resulting in a power consumption of 22mW at nominal ratings. Thus, at a power generation of 425W, the DC current sensing will consume far less than 1% of power. The supply voltage is rated for 3.3V and will be connected to the appropriate, available bus. The output voltage is proportional to the input current, which can then be sent to an analog input pin of the microprocessor.

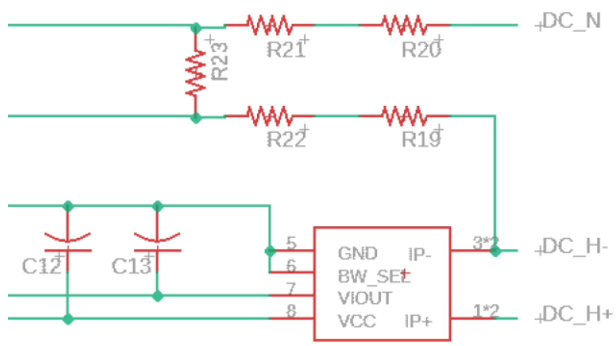

Figure 3: DC Sensing Schematic

2.3 Microcontroller + WiFi

The Particle Photon was chosen for the Microcontroller + WiFi solution as it best matched our need for I/O pins in number and type, supports IDE's with deep WiFi libraries (Arduino), allows for external antennas (alternative to printed), and is sold at a competitive price point.

The SparkFun Thing and Adafruit Feather HUZZAH were close second choices due the market saturation of the ESP8266 MCU, but both were limited in IO variety and lacked the cloud support provided by Particle.

The Photon also provided a built-in battery charging circuit which greatly simplified our power circuits.

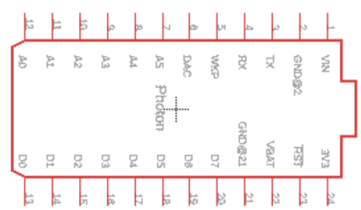

Figure 4: Particle Photon Schematic

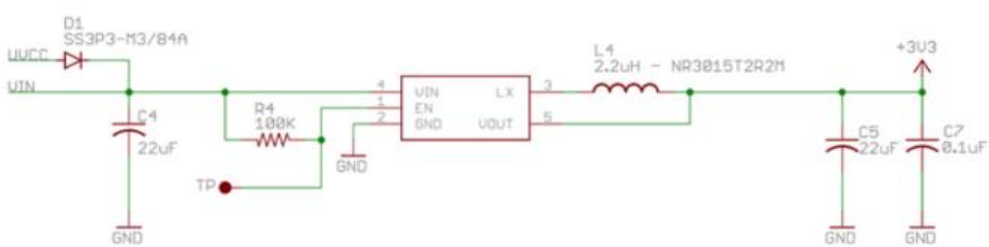

Figure 5: Photon Power Circuit

2.4 User Interface

The user interface consists of an electronic paper display and simple buttons.

2.4.1 Electronic Paper Display (EPD)

We used a 2.13" EPD manufactured by Pervasive Displays. EFD's have the advantages of extremely low power consumption (~5mW), low glare, and serialized communications (SPI).

We also considered Newhaven Display's 2-color displays, but these required a parallel to serial conversion, adding complexity while reducing update speed. These LCDs also have a stronger need for a backlight which would increase our power consumption.

2.4.2 Buttons

Our GPIO pins were limited by the need for two SPI buses, so we settled on two user buttons. This provides us with enough input patterns (presses, holds, double presses) to achieve a versatility user interface while reducing the failure risk points on the case.

2.5 Case

The case was built from a solid block of Aluminum. The block was milled out so that there was room for the PCB. Then a trench was milled so the O-Ring can be placed to create a seal. Two holes were drilled into the side of the case so that the wires can exit the case. (Two holes were drilled in case there wasn't enough room in one hole for all the wires.) These holes had special junctions that had rubber seals so that the wires may be sealed as they exit the case. Then a clear piece of plastic is screwed onto the side with the O-Ring. The plastic presses onto the O-Ring and creates a watertight seal.

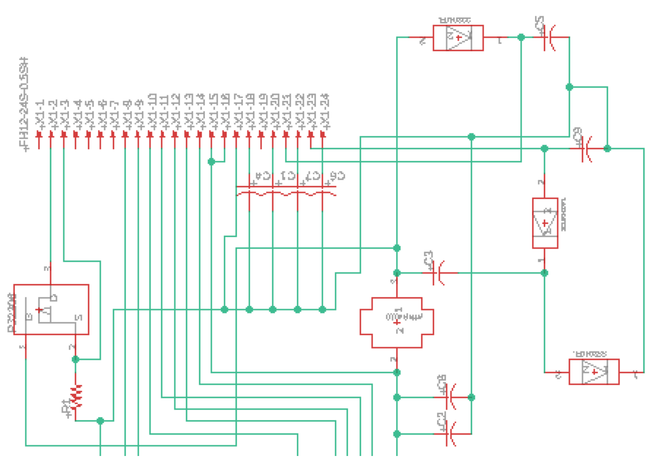

Figure 6: EPD Schematic

3. Design Verification

In order to measure the success of our device we ran multiple tests to verify that our high-level requirements. We also ran other tests to measure the quality and efficiency of our device. For notation, here are the labels we use:

Table 1: High-Level Requirement Notation

Label	High-Level Requirement
High-Level Requirement 1	Be able to measure AC and DC Voltage and Current
High-Level Requirement 2	Be able to send data via WiFi
High-Level Requirement 3	Be able to work in all weather conditions

3.1 High-Level Requirement 1

Most tests on the sensing equipment were conducted with small inputs as to not stress the power sources and to verify that the board can withstand moderate values. First, each value is tested separately. For the DC measurement test setup, a GPS-4303 Laboratory DC Power Supply and a power resistor bank, configured for 6 Ohms, were used. The DC source was able to supply up to about 30V and 3A. A third of each limit was applied in the initial test. The AC measurement test setup involved a Variac controlling a wall outlet's voltage and the same power resistor bank with the same configuration. Only $10V_{RMS}$ and $1A_{RMS}$ were used initially. The measurement data was sent over WiFi from the microprocessor to the PC as cloud variables. The values were read on the PC terminal, recorded, and compared to the source value, for DC values only, and a fluke meter. The results for DC voltage are shown in Figure 7: Low DC Voltage Test ResultsFigure 7. Percent error attributes to the accuracy of the measurement. The percent error for the DC voltage test is shown in Figure 8. The results for the remaining quantities can be found in Appendix A Requirement and Verification TableB.

The goal here is to verify that the percent error is decreasing for increasing input values, since the expected values will be at much higher values. Our results demonstrate that the error, even at these low values, becomes manageable considering the measurement signal processing has not been calibrated. The largest discrepancy is found in the device's AC current values. This may be caused by testing with such a small value of $1A_{RMS}$, since the maximum current the IC can handle is $30A_{RMS}$. However, when referencing the direct measurements, the scaling of the current signal may be modified to improve the accuracy near values of $3.5A_{RMS}$.

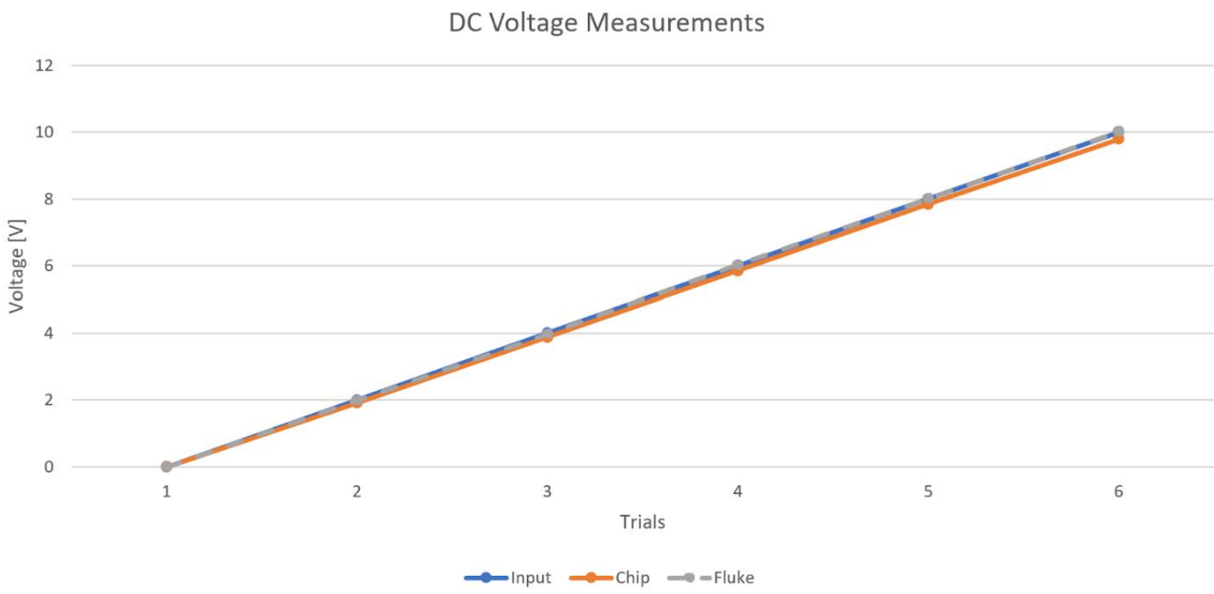

Figure 7: Low DC Voltage Test Results

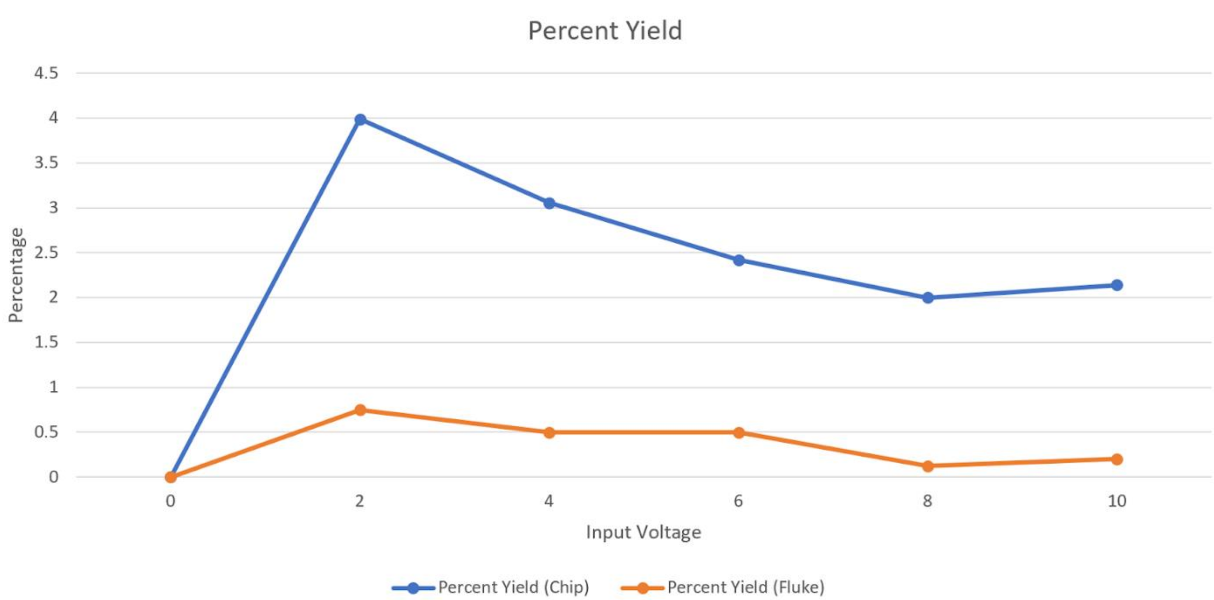

Figure 8: Low DC Voltage Test Error Results

The next test involves driving the sources to their limits and verifying that the device can measure higher values. The top measured values are provided in Table 2.

Table 2: Maximum Values Tested

AC Voltage (V_{RMS})	AC Current (A_{RMS})	DC Voltage (V)	DC Current (A)
116.5	3.496	31.28	3.202

We also verified that the board can register measurement results for all four values at the same time by taking video evidence [7].

Thermal images of the board after certain tests were taken to verify that there was negligible power dissipation in the sensing networks, which can be found in Appendix C Thermal Imaging Results.

3.2 High-Level Requirement 2

When we first received the Photon, our priority was ensuring the WiFi integration was functional. Early tests with barebones code proved that both strings and numbers could be accessed very easily with a PC on the same network.

This code was developed further to format our information and provide constant updates on values. Values can be easily accessed with either a PC or cellular device.

3.3 High-Level Requirement 3

The case was put under a shower and a sink (specifically spraying the edges) and no water leaked into the case. The case was also put into a box of dirt and shaken to show that no dirt would enter the box. These tests are similar to achieving a NEMA 3R rating. However, our case is also technically submersible in water, something that is not required for a NEMA 3R rating. We say *technically* because it is built so that the device can be used while under water, but we did not test this explicitly for safety reasons.

4. Costs

4.1 Labor

We can estimate our labor costs assuming roughly 10 hours of work per week (2 hours per day, standard work week). The current average salary for an entry level electrical engineer in Illinois is $54,713.00 or roughly $23.30/hr. [8].

$$23.30 \frac{\$}{hr} \times 10 \frac{hr}{wk} \times 16\, wks \times 3 = \$11{,}184 \tag{4.1}$$

4.2 Parts

Table 3: Costs

Part	Cost (Inv.)	Cost (Bulk)[1]
MPU (Amazon, Particle Photon)	$19.00	$19.00
E-Paper Display (DigiKey, E2213CS091-ND)	$14.34	$7.78
Enclosures[2]	$20.00	$10.00
3.7V Li-Ion Battery (Amazon)	$7.95	$1.33
AC Monitoring IC (DigiKey, ACS71020)	$5.09	$4.49
DC Monitoring IC (DigiKey, ACS722)	$1.97	$1.97
TOTAL:	$68.35	$44.47
WITH LABOR:	$11,252.35	$11,228.57

[1] Mirrored costs are due to the inability to find bulk pricing on some units

[2] Factory production estimates

4 Schedule

Table 4: Weekly Schedule

Dates	Cole	Joe	Matthew [3]
10/7 - 10/13	Begin developing code for WiFi communication	Design DC Voltage Divider and implementation of sensing ICs in Eagle	Design PCB Power Supply module
10/14 - 10/20 [4]	Begin developing E-paper screen driver code	Develop code for processing digital output of sensing ICs	Test Battery Charging Circuit
10/21 - 10/27	Test E-paper screen w/ MCU for basic measurement display	Include protection circuit and test the output of Measurement, prepare it for MP	Integrate the Battery + Charging Circuit with the DC/DC convert use to power the MC
10/28 - 11/3	Develop GPIO code architecture for measurement data	Perform individual tests for Measurement section.	Test the power supply module separately from the other modules (Debug)
11/4 - 11/10 [5]	Begin testing integration of measurement modules w/ MCU module	Integrate Measurement section with MCU, handle processing of measurement signals.	Integrate Power Supply Module with MCU module
11/11 - 11/17	Finish full integration testing with other modules	Finish full integration testing with other modules	Finish full integration testing with other modules
11/18 - 11/24	Develop general data organization/analysis program (MATLAB)	Develop data analysis program	Collect data on the performance of the power supply module
11/25 - 12/1	Fall Break	Fall Break	Fall Break
12/2 - 12/8	Final Demo	Final Demo	Final Demo
12/9 - 12/15	Final Presentation	Final Presentation	Final Presentation

[3] After the power module was absorbed into the processor, Matthew began working on the case and construction/testing of the PCB

[4] Focus was placed on integration with the measurement modules over the display at this phase

[5] Multiple delays and issues with PCB size caused a set back at this phase, removing the possibility to develop user software

5. Conclusion

5.1 Accomplishments

The current state of our design achieves all our high-level requirements. Demonstration testing has proven the device's ability to safely measure the nominal voltages and currents of our target solar panel. Our Cloud data solution is simple to use and access without pricey, proprietary software while providing useful and easy to understand information. Our case provides more than enough protection from the outdoor elements to keep our users and device safe.

This design can still be improved upon, but it provides a strong core of intelligently selected elements which together combine to form an innovating, user friendly, monitoring solution.

5.2 Uncertainties

We were unable to see successful results out of our EPD module. This is because we failed to implement a power switch (in the form of a transistor) to allow for updates of the screen frame. Even with these updates, using this EPD module may have been difficult. The documentation on the frame update procedure was convoluted and poorly translated. In future designs, a Newhaven Display model can be used with a new driver circuit. This would possibly reduce screen update time, but this is not a strong limiting factor.

We believe that, with calibration to account for tolerances on the resistor networks as well as modifying the factory calibration, we could reduce errors on all our measurements. Calibration procedures require specific and expensive equipment, but these could be rented, or the process performed as a service by a third party.

5.3 Ethical considerations

5.3.1 Safety

Our solution is intended to be operated by personnel in normal outdoor weather conditions. This creates many potential hazards in terms of damage to equipment and/or operators.

Foremost, our terminal box connects directly to the AC side of the inverters for the panels. In some systems, this could be directly tied to the supply side of a facility's utility connection. This requires that we follow strict guidelines created by the NEC, specifically those in NFPA 70. Section 110 covers general requirements for electrical devices, but our project will need to adhere to more strict regulations in sections 690, 691, and 705 which provide relevant standards for grid-tied PV installations. Section 690 covers circuits connected to PV installations (690.8.A.2), over-current protection (690.9), disconnects (690.15), wiring (690.31), and grounding (690.41). Section 691 covers additional requirements for large scale PV installations. Section 705 covers general grid-tied connections [9]. While each PV system may not require adhering to all these standards, the versatility of our solution requires that we follow the strictest practices.

Our design will meet these standards by attention to detail in the PCB design. Trace widths will be wide enough to handle higher current levels on inputs from the panel and inverter. Special care will be taken in trace buffers (the distance between two traces) to avoid arcing from high voltage potentials. Consideration will also be made in plane buffers (distance between the ground plane and top plane for example) to avoid arcing in the vertical dimension. Properly rated fuses and varistors will be installed to protect against overcurrent and transient conditions respectively.

Furthermore, both our enclosures (monitoring device and terminal box) must be able to withstand weather conditions. The enclosures must meet at least NEMA Type 3 specifications, with the terminal box requiring the strictest standards, Type 6 or better. These specifications cover outdoor enclosures and their resilience to water, ice, and particle ingress [10].

5.3.2 Ethics

Our design should follow the Ethical Engineering Code proposed by the IEEE council. Most notably, #9: "to avoid injuring others, their property, reputation, or employment by false or malicious action.'' Following the above safety standards will assist us in making sure our solution is safe for personnel handling and equipment installation, but we must consider the safety of persons and property with each device element. This means performing testing for worst case conditions and always assuming the worst-case scenario, as in our verification testing for the enclosures. Additionally, since our device collects and transmits data, we must adhere to #5 and #6 by assuring that our data is reliable and improves the development and use of PV installations [11]. It will be difficult to prove our data improves PV installations in the timeframe of the course, but we are assuring <1% error in our measurement data.

5.4 Future work

The larger system in which our measurement device exists is yet to be realized. The terminal block still needs to be manufactured and tested for environmental resistance as well as for electrical protection. An on-unit user interface in the form of a display and buttons would assist in the ease of use and data organization.

We also envision open-source data collection software which could collect results in a user-friendly format (plaintext, spreadsheet, etc.) This would enable inexperienced users to analyze long term performance and trends of their installation.

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Appendix A Requirement and Verification Table

Table 2: Requirement and Verification Table

Requirement	Verification	Status
Battery		
1. Rechargeable	1. Measure the battery's initial voltage. Then discharge the battery safely, measure the voltage. Then recharge the battery and re-measure the voltage over the battery.	1. PASS
2. Consistent 3.7V	2. Measure the voltage over the battery and see that it has a consistent 3.7V. Be sure to measure any noise created. (The noise level must be in the acceptable range of the MCU)	2. PASS
Charging Circuit		
1. A circuit that will safely charge the 3.7 V battery over time	1. Once, the battery is discharged, it is no longer producing the voltage and current it is supposed to, the charging circuit makes the battery have a full charge (4.2 V).	1. PASS
2. Charging stops once it is fully charged	2. When the battery is back to 4.2 V check that the MCU is no longer charging the battery.	2. PASS
3. Charging takes a reasonable amount of time to charge	3. Completely discharge the battery and then begin charging the battery while timing how long it takes to finish charging. (With the given ratings, it shouldn't take more than an hour)	3. FAIL
4. Charging will not occur in unsafe conditions	4. If the voltage and current is ever at an unsafe value (above 4.2 V) the charger will not work	4. PASS

Terminal Box		
1. Meets NEMA Type 6 standards to resist weather conditions throughout the year	A. Place anhydrous, color changing powder in case, submerge in water for 1 hour, check contents for signs of water B. Place in a box of small particulates (wood shavings, dirt, etc.), shake vigorously for 5 minutes, check for ingress C. Wet surface lightly with wet cloth, freeze overnight, repeat B, C	A. PASS B. PASS C. PASS
AC Power Monitoring		
1. At rated line side voltage and current ratings of the inverter, the digital output will have a voltage that is less than 1V.	1. Produce nominal currents that will occur pseudo-adjacent to hall effect-based sensor, verify negligible output current reading. Produce input linear and exponential signals for voltage, verify appropriate output shape in gathered data.	1. PASS
2. The power dissipation in the voltage divider's resistors will be considerably less than rated value.	2. Test integrity of temperature compensation sensing and logic and the power dissipation with external temperature readings and performance measurements.	2. PASS

Protection Circuit		
1. Fuses rated to create an open circuit when current levels are too high 2. Varistors to block voltage transients and create open circuits with prolonged overvoltage conditions 3. Output of protection circuit does not exceed current or voltage ratings of microcontroller	1. Produce short circuit conditions to blow fuses. 2. Produce peaks above rated input of protection circuit to simulate transients. Ensure circuit returns to steady state conditions. 3. Measure output of protection circuit with oscilloscope during transient simulation.	1. UNTESTED 2. UNTESTED 3. UNTESTED
DC Sensing Voltage Divider		
1. A circuit that takes the DC voltage, from the Solar Panel, and steps it down to less than 1V for the microcontroller 2. Power dissipation among resistors are low	1. Perform a DC sweep across input of circuit up to an output of 1V, compare results to voltage division scalar. 2. Measure current in network and heat of resistors after prolonged operation.	1. PASS 2. PASS
DC Current Sensor		
1. A circuit that takes the DC current, from the Solar Panel, and converts the signal to a proportional output voltage of less than 1V for an analog value to the microcontroller.	1. Perform a DC current sweep across input of circuit, compare processed data with input sweep. Verify possible adjacent currents are negligible in measurements.	1. PASS

Microcontroller + WiFi		
1. Converts analog metrics to organized digital data with no more than 1% error 2. Communicates over WiFi using IEEE 802.11b/g/n	2. Connect a 500 mV DC signal to the MCU and a measurement device with < 1% error; confirm matching measurements to error limit 2. Using pre-built WiFi libraries, connect to 2.4 GHz WiFi network and send "Hello World!" to a terminal	1. PASS 2. PASS
Electronic Paper Displays		
1. Readable outside, under direct sunlight 2. Readable from viewing angles up to 60°	1. Display Snellen Chart characters, holding screen outside at noon, ensure characters of at most ¼ of screen resolution (53 x 26) are readable 2. Repeat above test with screen rotated 60°	1. UNTESTED 2. UNTESTED
Buttons		
1. When installed, do not reduce the weather resistivity of the case	1. Repeat case verification testing with buttons installed	1. UNTESTD

Appendix B Additional Measurement Verification Results

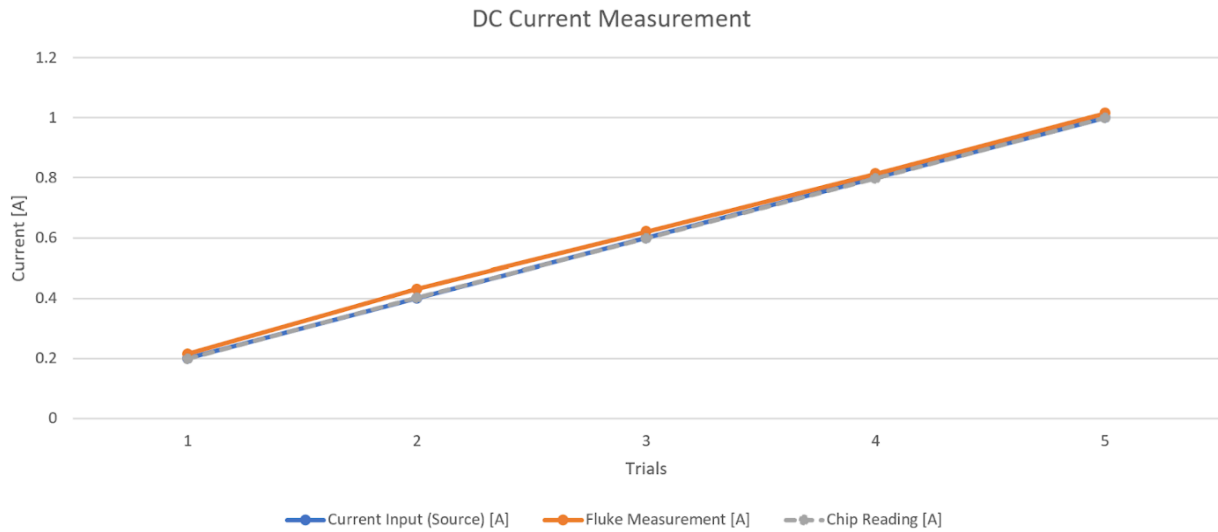

Figure 9: Low DC Current Testing Results

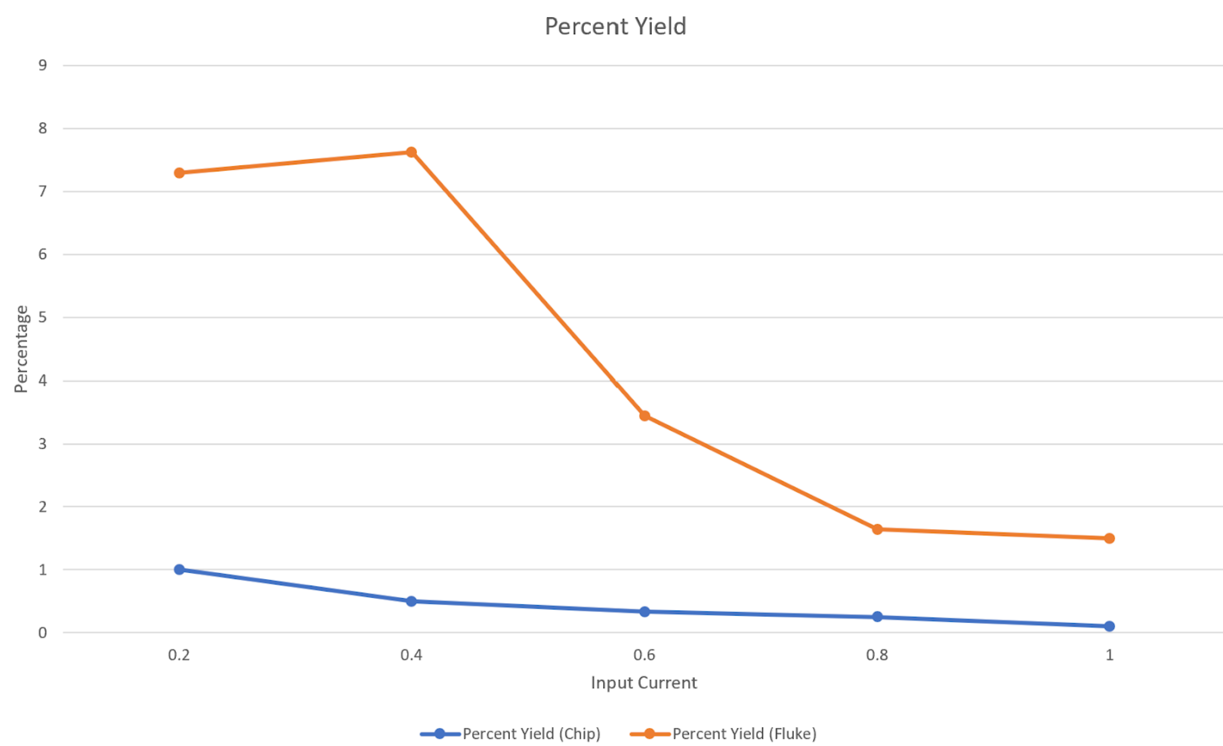

Figure 10: Low DC Current Test Error Results

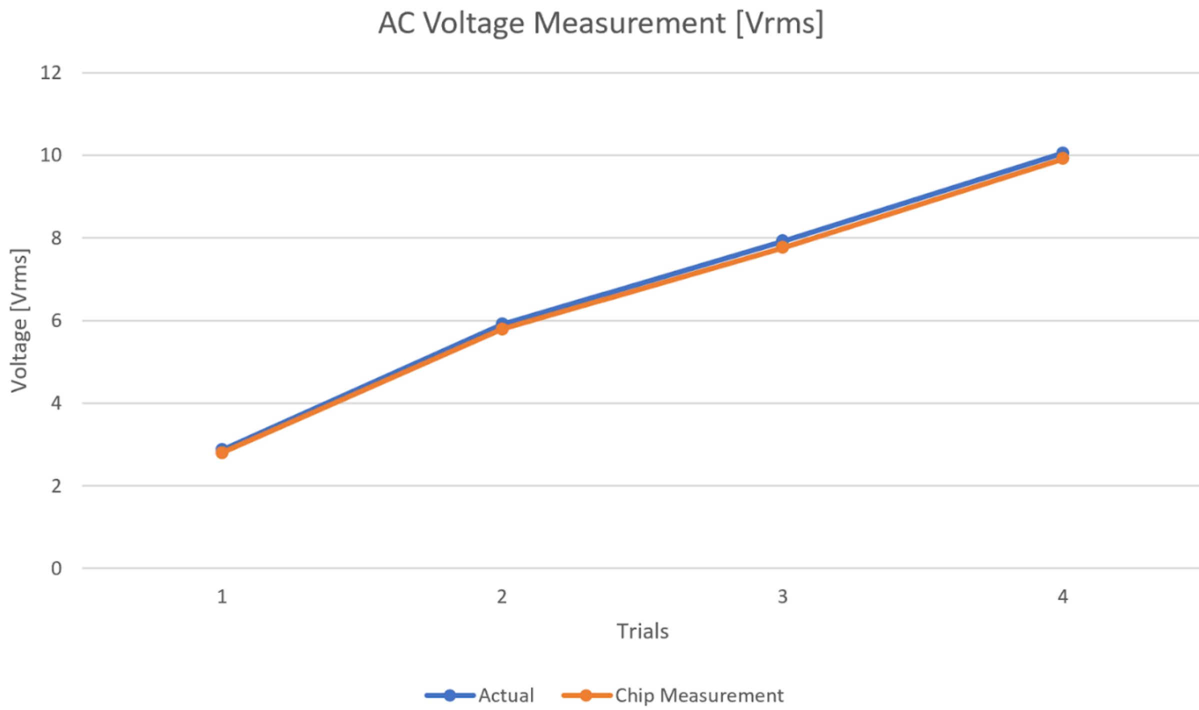

Figure 11: Low AC Voltage Test Results

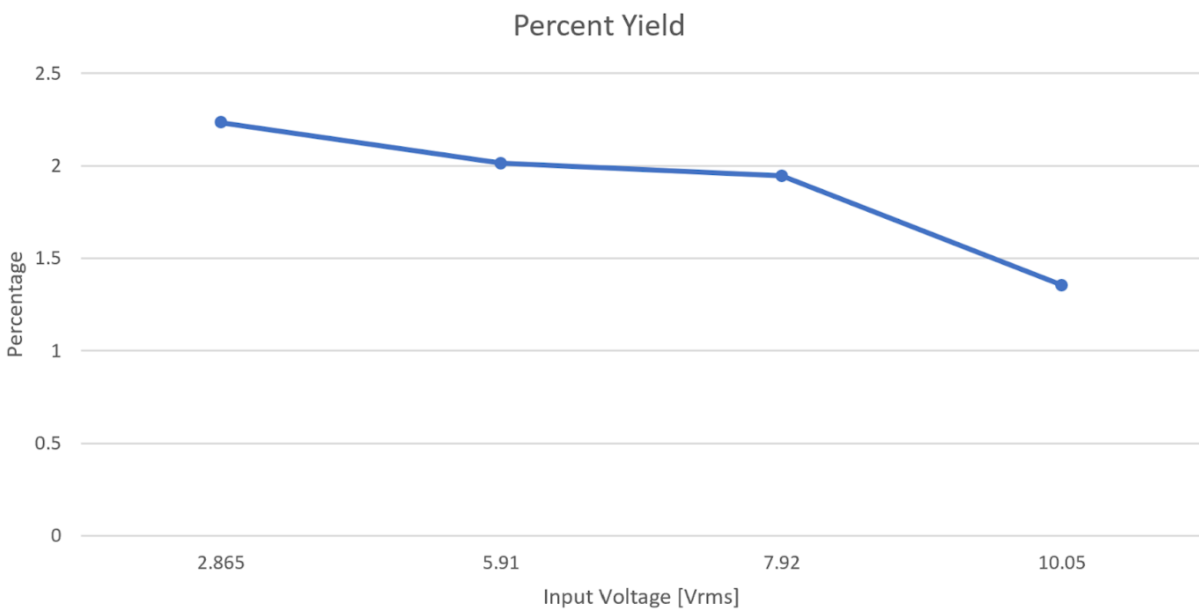

Figure 12: Low AC Voltage Test Error Results

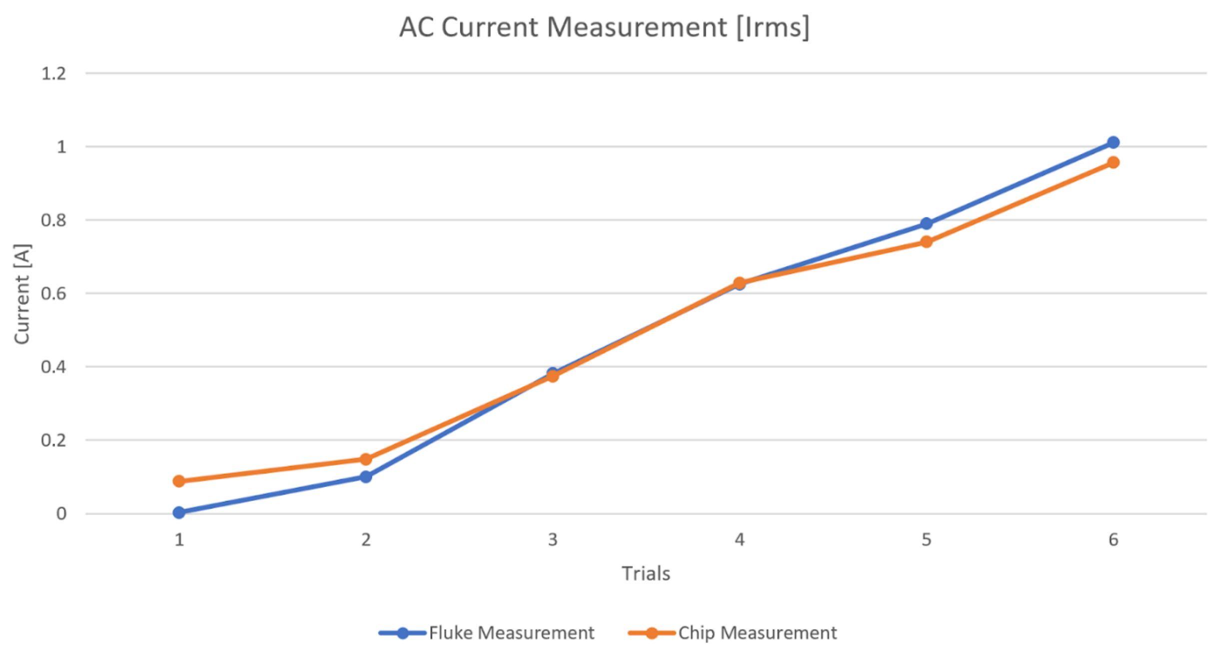

Figure 13: Low AC Current Measurement Test Results

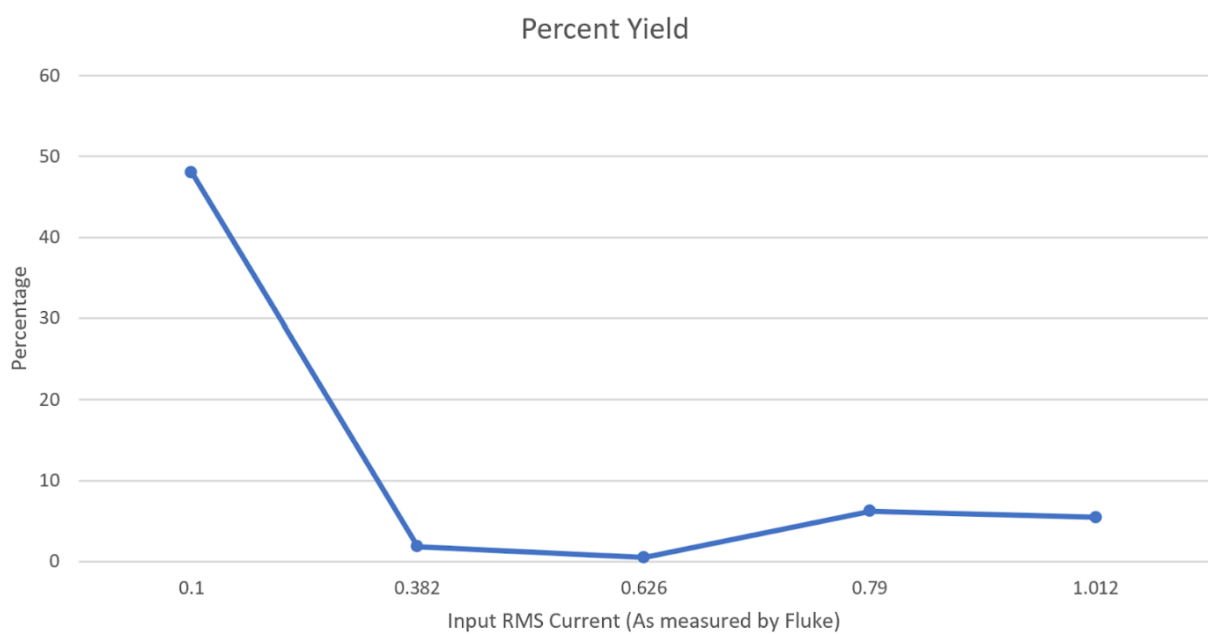

Figure 14: Low AC Current Measurement Test Error Results

Appendix C Thermal Imaging Results

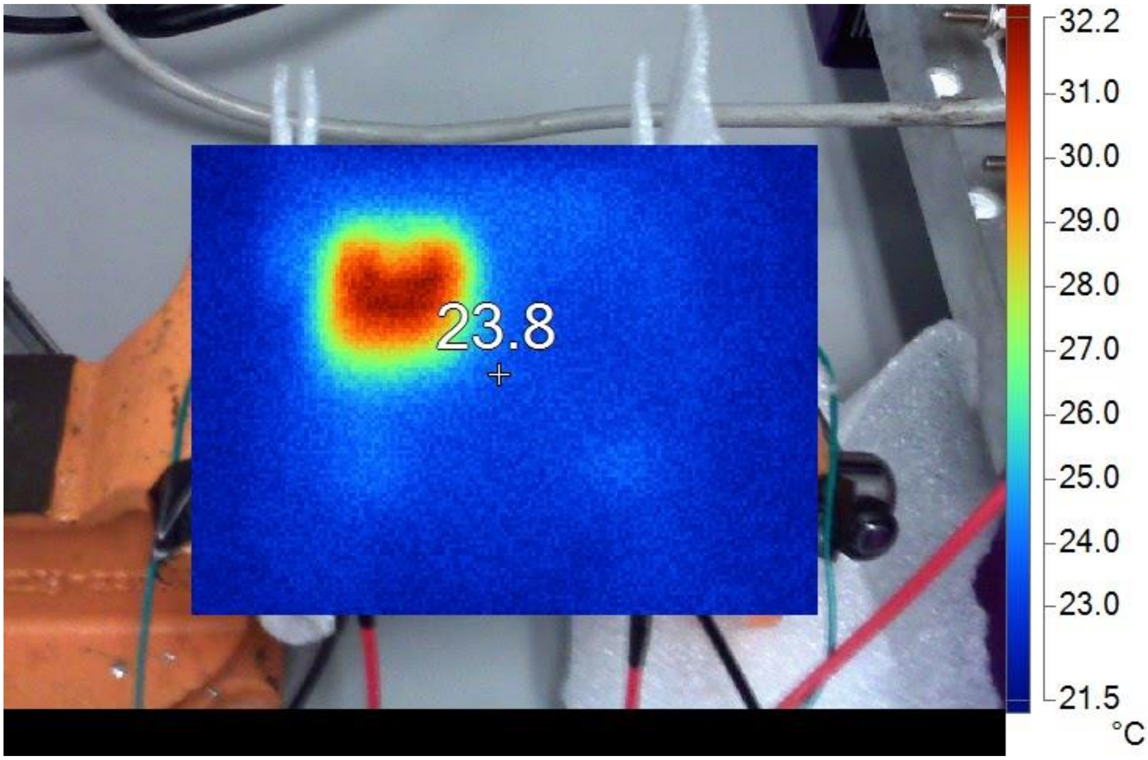

Figure 15: Thermal Image with 1A DC Input

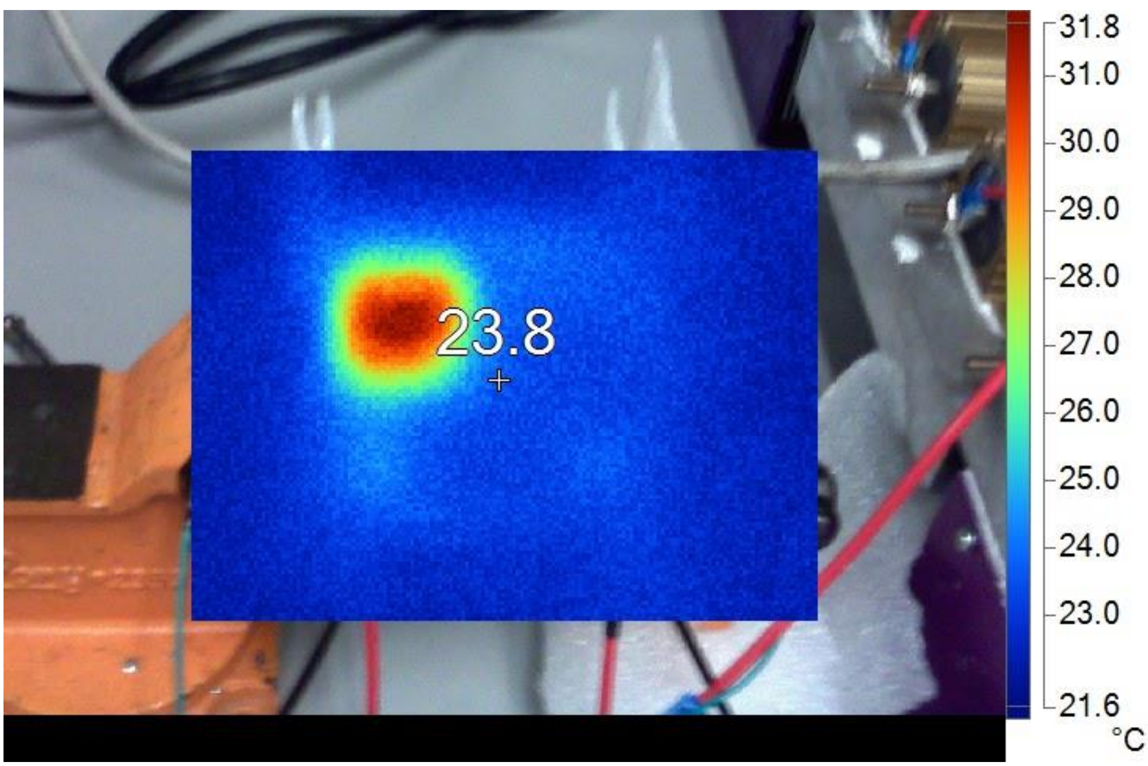

Figure 16: Thermal Image with 1A RMS Input

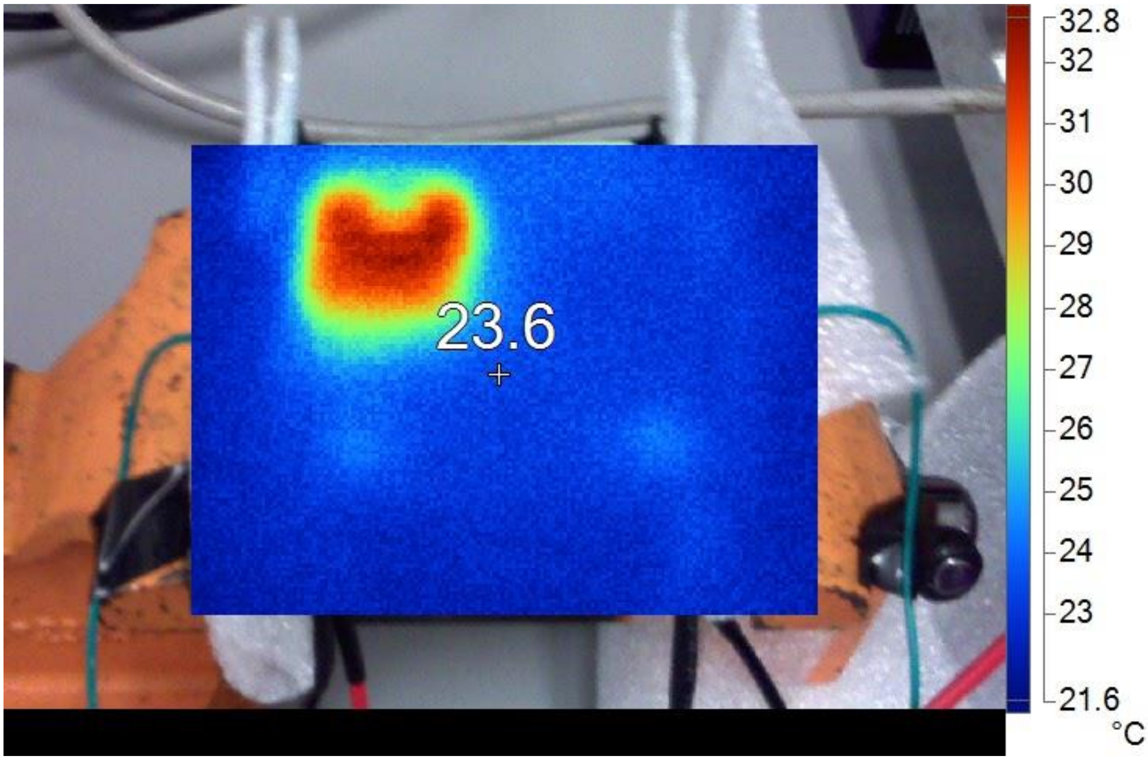

Figure 17: Thermal Image with 3.5A RMS Input

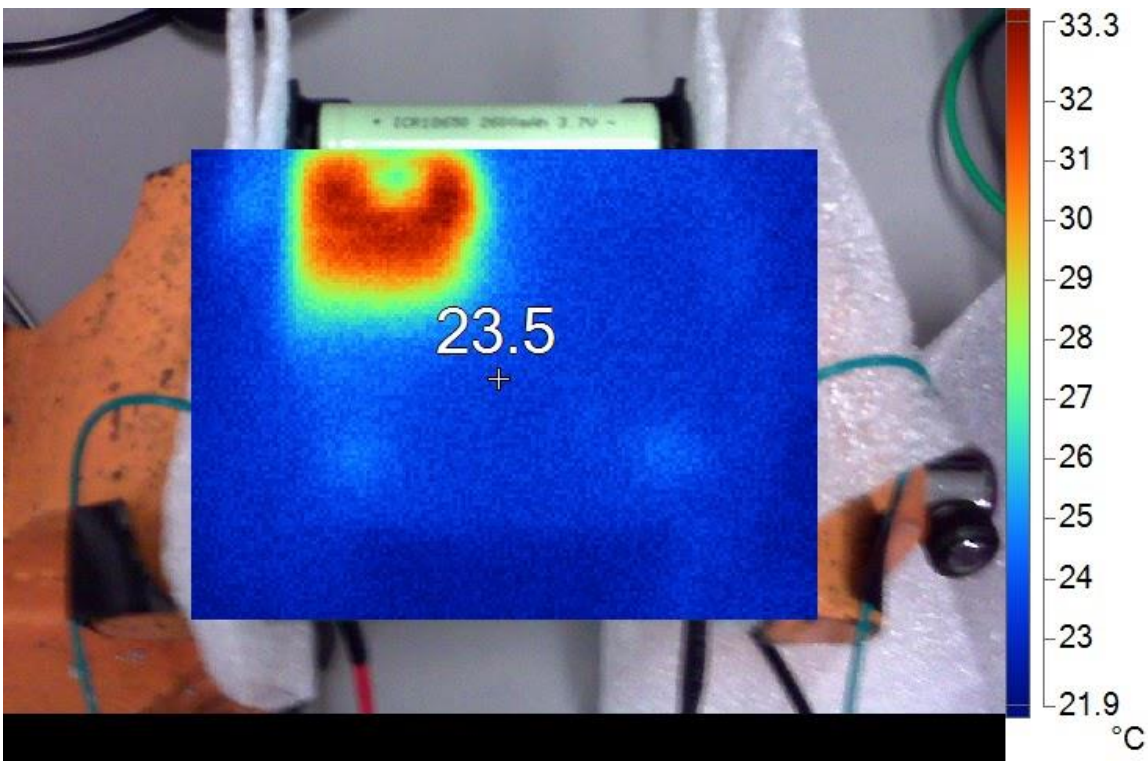

Figure 18: Thermal Image with 3.2A DC Input

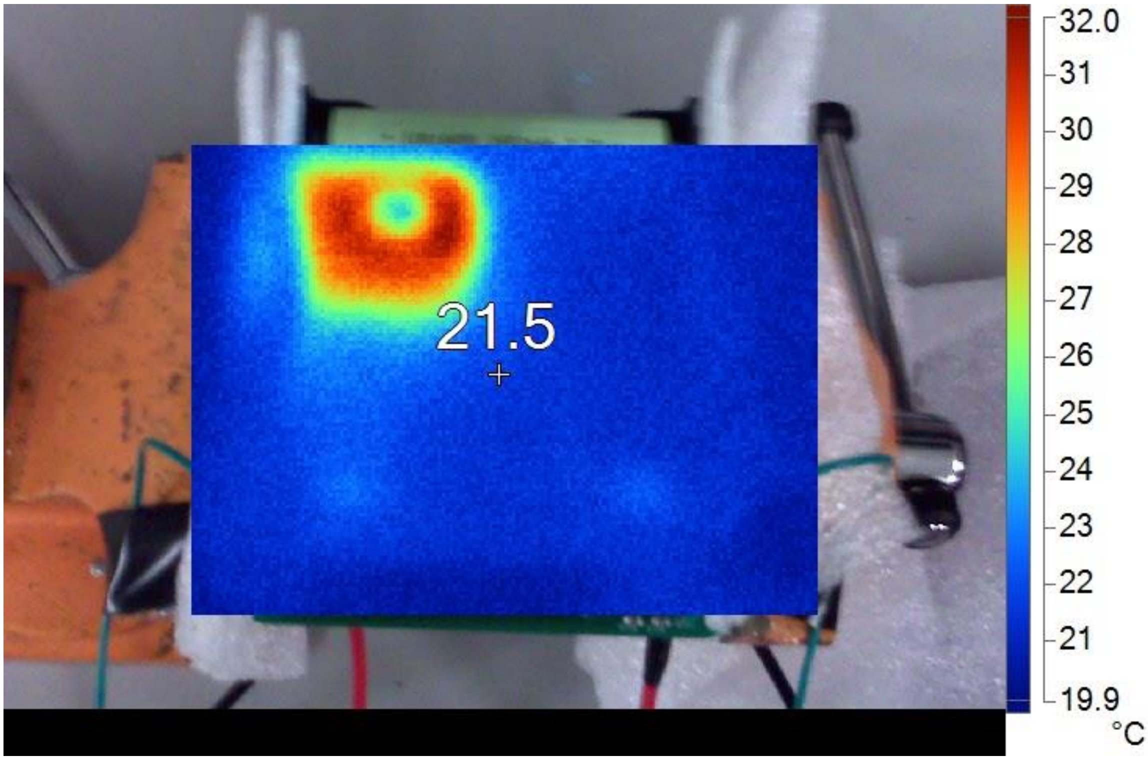

Figure 19: Thermal Image with 32V DC Input