ECE 445: Senior Design Laboratory

Fall 2021

Advanced Interface Box for Solar Panels

Design Documentation

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Contents

1. Introduction 1
   1.1. Problem Statement 1
   1.2. Solution Overview 1
   1.3. Visual Aid 2
   1.4. High-Level Requirements 2
2. Design 3
   2.1. Block Diagram 3
   2.2. Subsystem Descriptions 4
      2.2.1. Switching Subsystem 4
      2.2.2. Manual Switches 4
      2.2.3. OLED Display 4
      2.2.4. Thermocouples 5
      2.2.5. Wireless Microcontroller 5
      2.2.6. Remote External Portal 6
   2.3. Subsystem Requirements and Verifications 7
   2.4. Supporting Material 9
      2.4.1. Mechanical Design and Mounting Diagrams 9
      2.4.2. Mechanical Design and Mounting Explanation 11
   2.5. Tolerance Analysis 11
   2.6. Protection Methods and Analysis 12
3. Cost and Schedule 13
   3.1. Cost Analysis 13
   3.2. Future Schedule 14
4. Ethics and Safety 17

4.1. Ethical Issues ………………………………………………………………………... 17

4.2. Safety Concerns ……………………………………………………………………... 17

4.3. Safety and Regulatory Standards ……………………………………………………. 17

5. Conclusion …………………………………………………………………………………... 19

5.1. Success Criteria ……………………………………………………………………... 19

6. References ……………………………………………………………………………………. 20

1 Introduction

1.1 Problem Statement

There are 60 solar panels on top of the ECEB building, currently being used for research, which are not producing any power as of now and can potentially be integrated into the power grid. Additionally, they are not adequately monitored at the moment and this poses a large hazard, especially considering there are no protection interfaces between the panels and their connections to the power inverter.

We want to design a smart interface box for these panels to allow for large-scale system behavior and output monitoring, as well as to support panel up-keep, to prevent any potential disasters like fires while also opening the possibility of future integration of these solar panels into other avenues. In previous semesters (FA19), a team of students were able to create an interface which was able to display a **single** panel's voltage and current, but the solution could not be scaled up to interface with multiple panels as is required. This previous solution attempt also now gives us a constrained size which we must utilize to communicate with multiple of these research solar panels.

1.2 Solution Overview

Our solution to monitoring and maintaining the research solar panels is a smart interface box that will interface with **multiple** solar panels to produce a single wireless gateway of panel information that feeds into a visually attractive Research Hub for observation and access to research panel data.

The system will be powered from an isolated power supply. The power generated by each monitored solar panel will run through our smart interface box, giving us the ability to detect overvoltage and overcurrent conditions and disconnect individual panels if necessary to prevent hazardous situations. Other features of the box will include reconfigurable tapping to allow users to determine which solar panels themselves are being observed. We will also provide the possibility of manual configuration of solar panels through a wireless interface, allowing users to configure and monitor the solar panel remotely through a server/PC. Finally, LEDs will be used on the box to indicate the dynamic status of panels as well as the interface. As a fail-safe for remote management of the interface being unavailable, the configuration of the interface can also be controlled manually via onboard switches.

1.3 Visual Aid

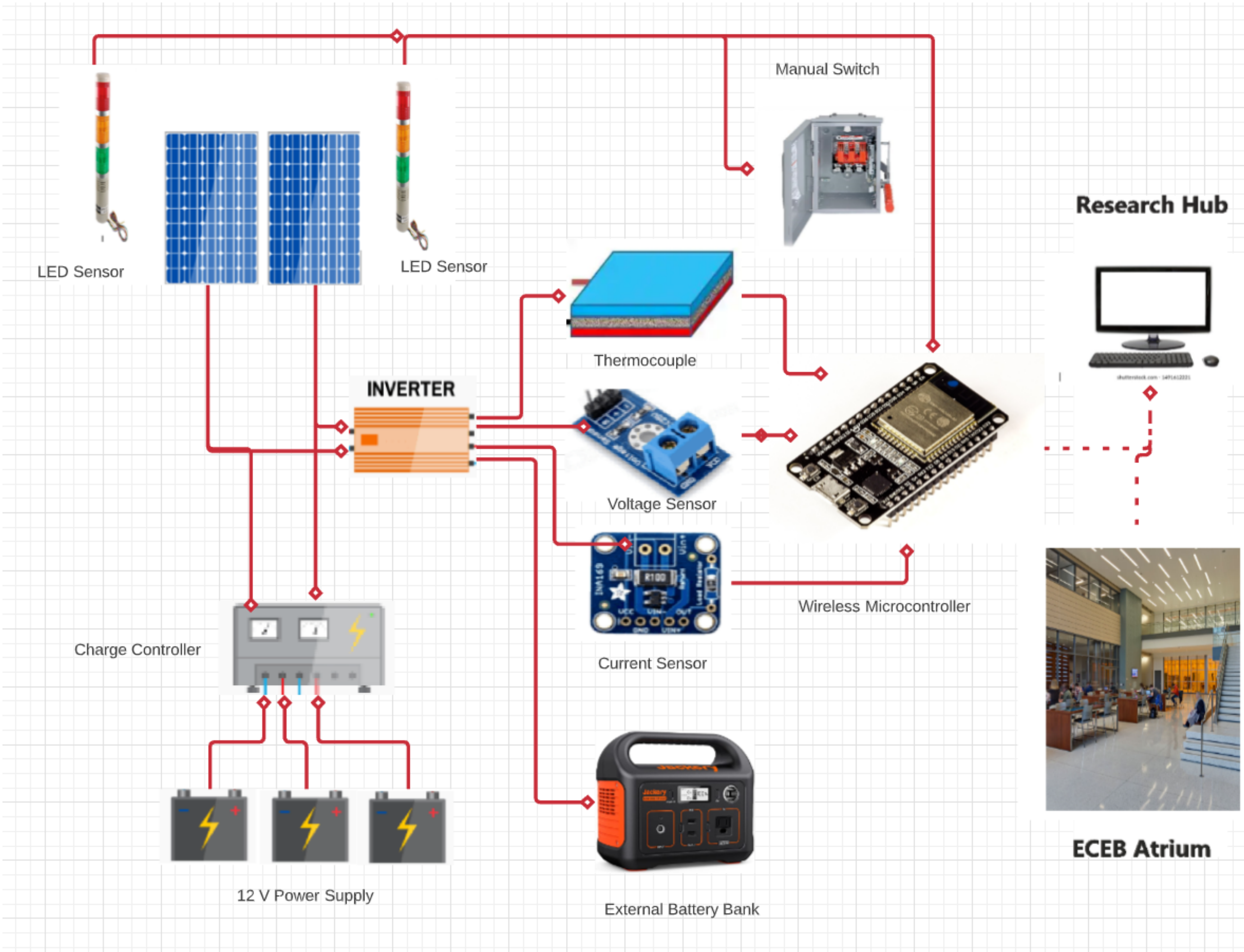

Figure 1: Diagram of the connection between different components of the interface

1.4 High-Level Requirements

1. Recording 3 key solar panel data values - voltage, current, and temperature
2. Wireless communication capability with solar panels (with access portal)
3. Scalability - capability of interface box retrieving data and communicating with more than 1 solar panel

2 Design

2.1 Block Diagram

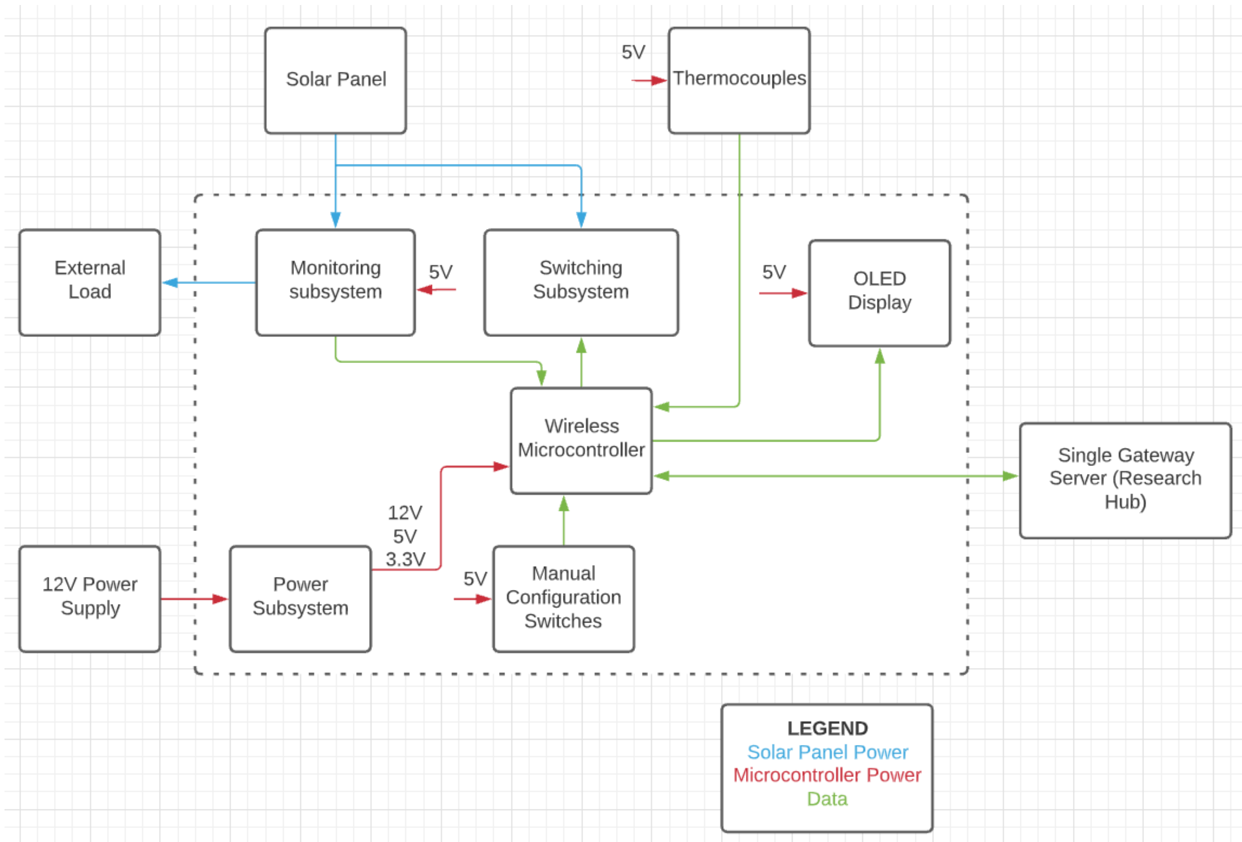

Figure 2: Labelled Block Diagram for Advanced Interface Box

Our block diagram provides a high level overview of how we expect to meet our high - level requirements. Our interface box, which is outlined within the dotted line, is made from 6 different subsystems: the monitoring subsystem, switching subsystem, OLED display, wireless microcontroller, power subsystem, and the manual configuration switches. These subsystems are discussed in section 2.2 below and are the backbone of our wireless communication and IoT interface. We chose to use a wireless user interface in order to complete our high level requirement of scalability and wireless connectivity. Within our interface box is also where we will be monitoring 2 out of our expected 3 measurements; current and voltage.

We will be monitoring our 3rd measurement outside of our interface box via our thermocouples. These will be mounted directly onto the solar panel at various locations in order to read accurately. The data collected will be fed into our microcontroller, which is within our box.

If our block diagram and its components are operating correctly, we expect our high-level requirements to be met and our project to be successful.

2.2 Subsystem Descriptions

2.2.1 Switching Subsystem

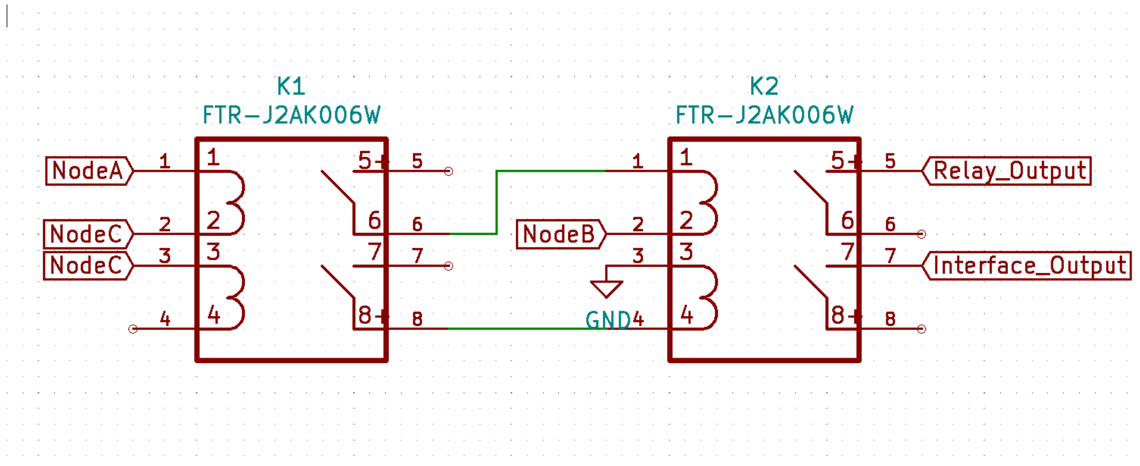

Figure 3: Relay system to configure which cells will be the current input

Relays containing the ability to reconfigure which sections of the solar panel are being displayed to the wireless interface. Combinations include 32-cells, 64-cells, and 128-cells. In order to be able to configure our switches properly we are utilizing two double pole double throw FTR-J2 Series Relays. These relays will be connected to I/O pins on our microcontroller, which will allow us to choose our output. These relays were chosen and given to our group as a design constraint due to the voltage and current protection they provide our solar panels. Our microcontroller toggle high and low is what enables the electromagnetic field of our relay to switch between outputs. This is what will allow us to attain the various combinations of solar cells we and the user will desire.

2.2.2 Manual Switches

For manual configuration of the interface box in which the wireless service access may be unavailable. The switches on the interface box can configure the solar panels and will be mounted on the enclosure. Most likely done through combinational or sequential logic depending on how much functionality we can implement

2.2.3 OLED Display

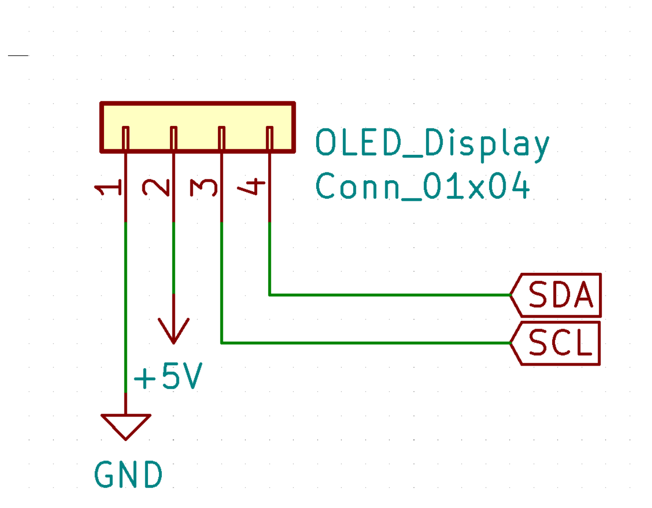

Figure 4: OLED display to visualize voltage, current, and temperature readings inside individual Attabox

Our OLED is what displays the current status of information gathered from the panels such as input voltage, current, and solar panel temperature. It also outputs two pins that connect to our microcontroller the SCL and SDA pins. The SCL pin is the clock line, this pin is used to synchronize our data as it is transferring over the bus. On the same bus is the SDA data line, which is used to transfer the data.

2.2.4 Thermocouples

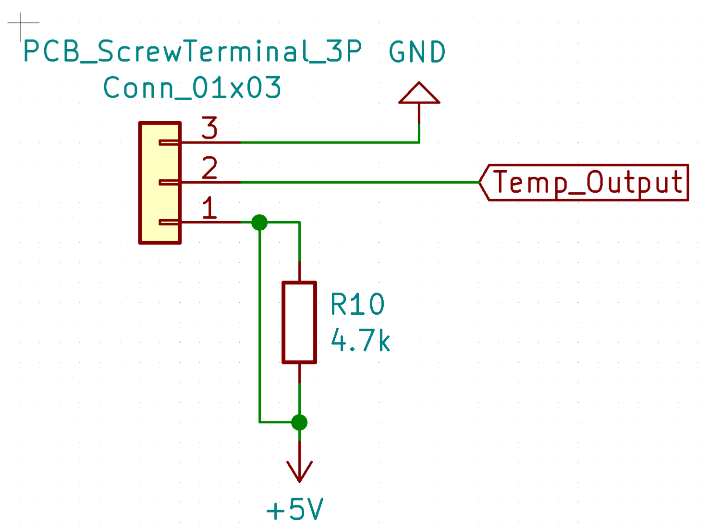

Figure 5: PCB design of utilizing a 3-pin PCB screw terminal to connect temperature output to ESP-32 microcontroller

Thermocouples operate in a parallel combination so that different areas of the solar panel can be monitored.

2.2.5 Wireless Microcontroller

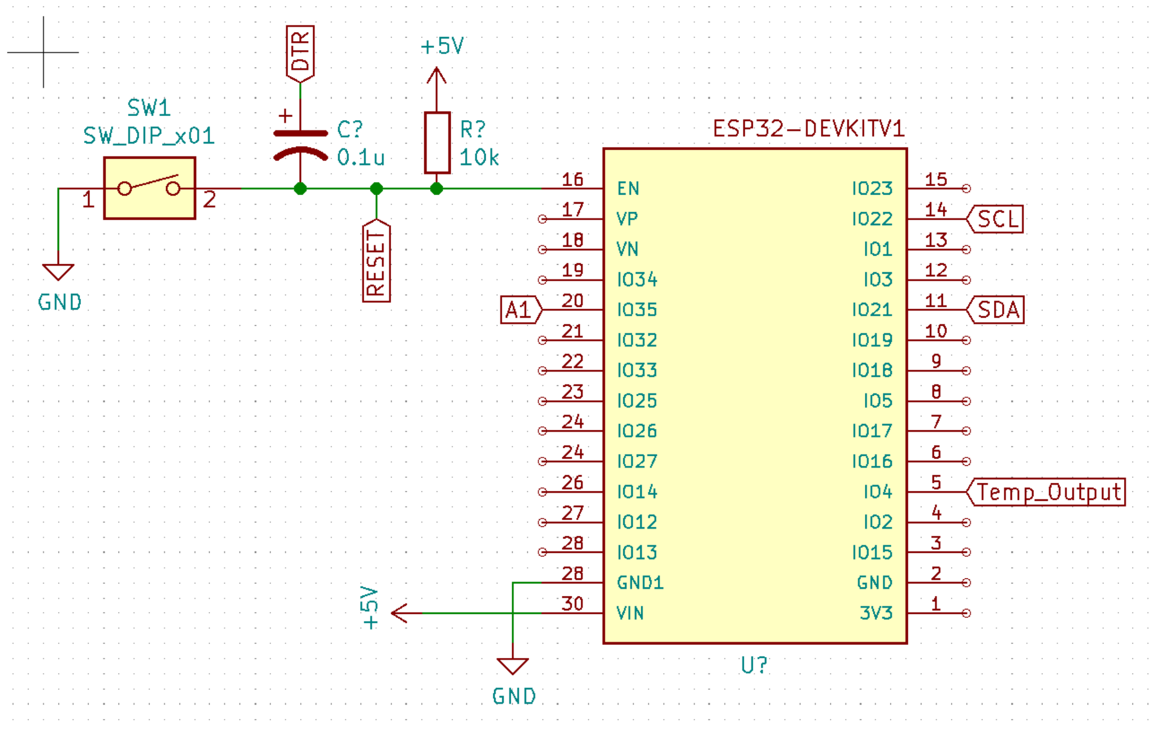

Figure 6: Microcontroller PCB Design - utilizing voltage and current input, enabled through an external manual switch

The main processor for our interface box which has functionality such as being able to communicate the data received from the solar panels, shut down its 12V operations or limit any protection from overvoltage/current, and to determine areas in which certain panels may be overheating. We plan on displaying additional data beyond that which may include detailed waveforms and power calculations to our display system.Brings about wifi functionality to push data at high speeds from the interface box to the research hub. In order to scale up the project to have our microprocessor communicate with multiple solar panels, there needs to be a wireless node network. We cannot strictly rely on wiring which communicates one panel's information, instead having a range of sensor nodes spatially dispersed to monitor and record the conditions of each individual solar panel which help bring in collective data to our display.

2.2.6 Remote External Portal

An external web-based server system - “Research Hub” - will be set-up with two-way communication with the box’s wireless network capabilities to allow for easy managing of the solar panels. Only authorized ECEB personnel will have access to this portal and it is intended for internal use, so the interface will be secured as such. The focus will be on porting the in-box button and switch capabilities to a remote setting for usage, as well as being able to receive and monitor key solar panel data points.

Relevant data for monitoring can be stored in a local external database, and a python-based framework will be able to extract and transmit commands for this effectively, while JavaScript/Java can also be used to build up the framework. REST API can be utilized for the back-and-forth data communication stream.

The communication link to the microcontroller will be further established using the on-chip network and its corresponding protocols (primarily HTTP).

➢ Wireless Panel Configuration: One of the two primary goals of this external portal is to port the physical switch-based fail-safe switch off capability and the microcontroller-based panel section adjustments for monitoring solar panels, so as to allow for remote access. Since these are controlled through the switching subsystem and relays, we will process user-specified configurations on the front-end to be sent through the microcontroller to the relay system.

➢ Data Visualization: The second goal of the external portal is that data collected and reported for monitoring purposes will be presented in an aesthetic manner on the access portal itself. A web-based visualization of the data could also then be adapted and provided for public display as well. Irrespective of final implementation, this too will be secured to only allow authorized ECEB personnel to control the data.

➢ Aesthetic data visualization itself can be achieved with a combination of Python-based data science tools along with HTML to build it up on a webpage. In the case of a separate display as well, once again, a python-based framework paired with JavaScript/Java and REST API-based communication can be used.

2.3 Subsystem Requirements and Verifications

Requirements [Points]	**Verifications**
Microcontroller [10] ➔ Communicate wirelessly with our display interface and display the data collaboratively with other data gathered from additional solar panels ➔ Retrieve voltage, current, and temperature readings	1. Physical verification of measurements of the 3 key solar panel data points 2. For safety and regulation - voltage, current, and temperature readings are accurate should not exceed ratings 3. Need to verify Access Point speed for different subsystems to ensure quick and reliable communication throughout the system
Switching Subsystem [15] ➔ Relays can configure which cells are being inputted into our voltage and current calculations ➔ Option to read no-input as a failsafe incase a reading trips the threshold	1. Retrieve an appropriate open circuit voltage dependent on which cells are input: a. A-D Configuration (128 cells) - expected open circuit voltage of 85.6V b. B-C Configuration (64 cells) - expected open circuit voltage of 42.8V c. C-D Configuration (32 cells) - expected open circuit voltage of 21.4V

Power Subsystem [15] ➔ Converts the 12V power supply unit into 12V, 5V, and 3.3V dc output with a buck-converter to power the microcontroller, sensors, etc.	1. Verification through inspection of input and output voltages: a. Measured values need to be within 100mV from their actual values
OLED Display [10] ➔ Displays the voltage, current, and temperature reading from the microcontroller to conveniently display each individual panel reading on the Attabox	1. Manual verification that readings from the microcontroller are in-line with the readings that are displayed on the OLED 2. Further confirmation of working - when input is not connected, no cells are generating power to the load and so we should get a voltage reading of 0V.
Wireless Communication System between External Portal and Microcontroller/Interface Box [15] ➔ There needs to be reliable 2-way communication between an external server and portal and the interface box to allow for remote observation and configuration ➔ This network will be made wireless and needs to ensure data received is translatable at both endpoints	1. External Server needs to be able to communicate both GET and POST requests wirelessly to microcontroller successfully (for 2-way communication) 2. Microcontroller needs to be able to communicate POST requests wirelessly to the external server successfully (for data monitoring) 3. Verify that microcontroller is able to process and translate configuration settings received a. Board level acknowledgement system's response can be used 4. Verify that external portal is able to receive and translate solar panel data for external monitoring: a. System verification of conversion to a mark-up language (XML or HTML)
On-Board Solar Panel Monitoring and corresponding Remote Portal Configuration [20] ➔ There needs to be physical switches for disabling panels as a fail-safe ➔ The microcontroller needs to be able to monitor and process 3 key data points from the solar panel output through Relays ➔ The external server and portal need to update based on measured data	1. Manually verify if fail-safe physical switches on the board can turn off the solar panels 2. Verify that Relays on the microcontroller are able to configure which solar panel section is being monitored: a. Adjust relays at interface-box-level to arbitrary solar panel sections b. Observe for variations in the 3 key outputs' values that reflect 3. Verify over the remote portal if user interaction through GUI results in the same two manual and controller based

➔ The external portal also needs to emulate all configuration capabilities found at the interface-box-level (remote access)	configurations mentioned above: a. electronic communication confirmation through HTTP b. physical reading confirmation at the interface box for microcontroller reaction
Solar Panel Data Monitoring and Visualization [15] ➔ 3 key data points need to be measured from solar panel output - voltage, current and temperature ➔ These measurements need to be visualized and monitored on a “Research Hub” external portal ➔ The external server needs to be secured with least-privilege access, and needs to update periodically to reflect solar panel conditions	1. Manually verify if Relays on the microcontroller are providing the 3 key output measurements as expected 2. Verify over the remote portal that key solar panel data being monitored and processed on the microcontroller: a. Utilize Javascript alerts to highlight every incoming data stream update b. Confirm data updates are aligned with microcontroller updates on the interface-box-level 3. Verify on the web front-end that periodic solar panel data updates are reflected as required: a. Visual verification on time-series portal information 4. Verify that research data can only be accessed by and panel configurations can only be adjusted by authorized ECEB personnel: a. Basic attack vectores should not be able to gain access to the portal (iterative testing) b. Saved profiles can log into, log out of, search, and edit configurations on the “Research Hub” portal (through UI/UX verification)

Table 1: Requirements and Verifications Table for the Project

2.4 Supporting Material

2.4.1 Mechanical Design and Mounting Diagrams:

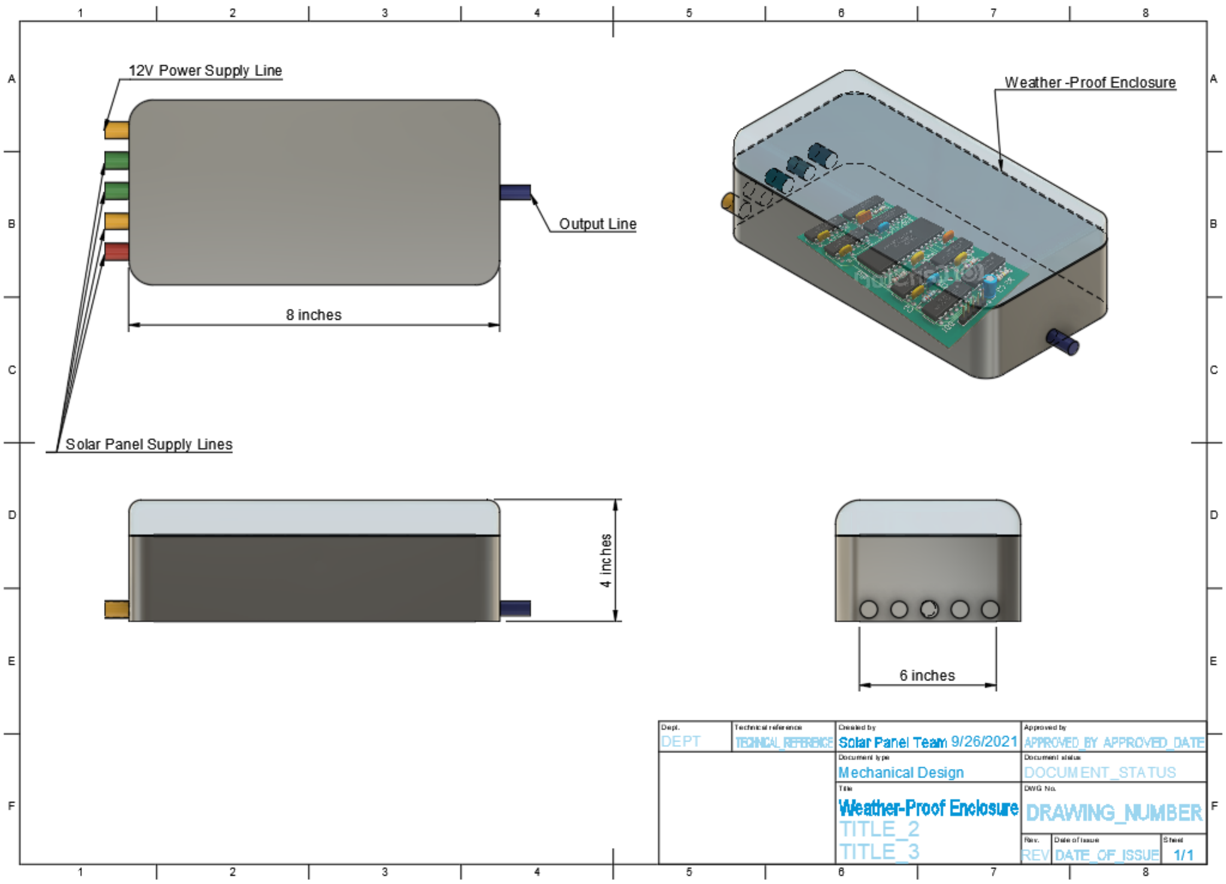

Figure 7: 3-D Visual Aid for the Box Enclosure

Figure 8: Mounted Attaboxes on the Solar Panels (Roof of ECEB)

2.4.2 Mechanical Design and Mounting Explanation

The mechanical design of our project is only our weatherproof enclosure. This was one of our design restraints when taking this project due to the weather proof enclosures already being purchased for the 60 solar panels. Our enclosure constraints are 8x6x4 inches as referenced from our enclosures part number [1]. This box is to be mounted on the solar panels on the roof of ECEB as shown in the Figure above. We know this is feasible as this design and mounting process have been implemented on 8 of the 60 solar panels that are currently being housed on the roof.

2.5 Tolerance Analysis

Our biggest risk while implementing this project is our ability to have a functioning wireless microcontroller that is able to communicate with our research hub and solar panels without the use of ethernet cables. The microcontroller we are planning to use is able to transmit data at 802.11n @ 2.4 GHz up to 150 Mbit/s. In contrast, an average, commonly used ethernet cord is able to transmit about about 100Mbits/s. While 50Mbits/s does not seem to be consequential, there are nearly 3.154e+7 seconds per year, meaning we would miss out on around 1577000000 bits per year per solar panel, which justifies the higher transmitter rating. Another risk that can be taken into account when analyzing our microcontroller is if our signal goes down and we are unable to receive any data for a certain period of time. Thankfully, as all of Illinois is connected to the same signal, we are able to null the effects of our signal going down through the administrative end and focus on our microcontroller. If our microcontroller is not able to convey our measurement outputs to our research hub, we would immediately be able to tell through our visual LED aids. Again, we believe this risk can be justified by the safety and the environmental concerns that ethernet cables would hold in its stead.

2.6 Protection Methods and Analysis

While implementing our senior design project, safety and safe protection of the solar panels is a high priority. While there are already some safety mechanisms in place in order to protect the ECE building and its users from the solar panels such as:

- Failsafe button that is able to shut off power being drawn from all solar panels
- A electrically approved and powered panel that draws the solar panel outputs, each wire protected by a circuit breaker

We recognize that there is still danger in the solar panels being protected from one another. We would also like our solution to be implemented and therefore we brought forth two major safety measures for our design.

The first is manual switches that are able to shut down our design and stop pulling all measurements from the solar panel. While we will be attempting to implement a switch within our online program, we recognize the dangers of unstable WIFI, therefore we have manual switches that are able to stop our analysis on the solar panels instantaneously in case of an emergency.

In case of unstable online data, we also hope to connect physical LEDs on our solar panels. These LEDs will be able to visually communicate with viewers if our board is communicating correctly and is functioning. It will also be able to change colors to indicate if there is a problem with our designs functionality or if our design is not functioning at all.

3 Cost and Schedule

3.1 Cost Analysis

Part Name	Vendor	Vendor Part #	Manufacturer Part #	Quantity	Total
EVAL BOARD FOR ESP-WROOM-32	DigiKey	1965-1000-ND	ESP32-DEVKITC-32D	2	$10.00 x 2 = $20.00
SENSOR CURRENT HALL 20A DC	DigiKey	SEN-13679 ROHS	ACS723LLCTR-20AU-T	2	$4.46 x 2 = $8.92
GROVE - OLED DISPLAY 0.96" (SSD1)	DigiKey	1597-104020208-ND	104020208	2	$4.30 x 2 = $8.60
WATERPROOF DS18B20 DIGITAL TEMPE	DigiKey	1528-1592-ND	381	6	$9.95 x 6 = 59.7
DIODE SCHOTTKY 40V 3A SMA	DigiKey	340A-FDICT-ND	B340A-13-F	6	$0.47 x 6 = $2.82
IC REG LIN POS ADJ 800MA SOT223	DigiKey	LM1117IMPX-ADJ/NOPBCT-ND	LM1117IMPX-ADJ/NOPB	4	$1.41 x 4 = $5.64
CAP ALUM 47UF 20% 25V SMD	DigiKey	493-9423-1-ND	UCW1E470MCL1GS	6	$0.54 x 6 = $3.24
CAP CER 10UF 25V X5R 0805	DigiKey	587-2985-1-ND	TMK212BBJ106KG-T	6	$0.21 x 6 = $1.26
CAP CER 0.1UF 50V X7R 0603	DigiKey	311-1344-1-ND	CC0603KRX7R9BB104	8	$0.10 x 8 = $0.80
CAP CER 1000PF 25V X7R 0603	DigiKey	311-3994-1-ND	CC0603JRX7R8BB102	2	$0.10 x 2 = $0.20
RES SMD 240 OHM 1% 1/10W 0603	DigiKey	YAG3582CT-ND	AC0603FR-07240RL	4	$0.10 x 4 = $0.40
RES SMD 1K OHM 1% 1/10W 0603	DigiKey	311-1KLDCT-ND	AC0603FR-071KL	6+4+4	$0.10 x 14 = $1.40
RES SMD 390 OHM 1% 1/10W 0603	DigiKey	311-390HRCT-ND	RC0603FR-07390RL	2	$0.10 x 2 = $0.20
RES SMD 4.7K OHM 1% 1/10W 0603	DigiKey	YAG3613CT-ND	AC0603FR-074K7L	2	$0.10 x 2 = $0.20
RES SMD 150K OHM 1% 1/10W 0603	DigiKey	YAG3567CT-ND	AC0603FR-07150KL	2	$0.10 x 2 = $0.20
RES SMD 10K OHM 1% 1/10W 0603	DigiKey	311-10KLMCT-ND	AF0603FR-0710KL	6+6+8	$0.10 x 20 = $2.00

RES 133K OHM 1% 1/10W 0603	DigiKey	RMCF0603FT133KCT-ND	RMCF0603FT133K	2	$0.10 x 2 = $0.20
LED GREEN CLEAR 0603 SMD	DigiKey	732-4980-1-ND	150060VS75000	4	$0.15 x 4 = $0.60
DEPEPE 30 Pcs 40 Pin 2.54mm Male and Female Pin Headers	Amazon	DE37566	0710280337566	1	$5.39
Primary PCB	PCBWay	-	-	2	$4.90 x 2 = $9.80
Weather Proof Enclosure	Amazon	-	-	2	$30.99 x 2 = $61.98
Cable Glands	Amazon	-	-	16	$0.40 x 16 = $6.40
MC4 Connectors	Amazon	-	-	12	$9.99/6 x 2 = $19.98
FTR-J2 Series Relay	Provided	N.A.	FTR-J2AK012W	4	$0
Total	-	-	-	-	= $219.93

Table 2: Parts to be bought for use (0 build hours)

As seen in Table 1 above, we will need a total of $219.93 budgeted to obtain the parts that we need for our project, i.e. to obtain the parts needed to construct 2 separate solar panel interface boxes.

Furthermore, this is a 4 credit hour class, which implies a minimum of 8 hours of work a week towards our project and its goals. In alignment with our future schedule planned for the remainder of the semester, we have 11 weeks or 88 hours of work ahead individually. Now, as per industry standard, UIUC Electrical Engineering undergraduates on average are paid $80,000 per annum, while UIUC Computer Engineering undergraduates are paid $100,000 per annum [2]. Allowing for some variance, we budget that each team member would be paid about $40 per hour as employees on this project.

So, as per the assigned class budgeting formula, our project cost would be: ($219.93) + [($40/hour) x 2.5 x 88 hours] = $9019.93 ≅ **$9100**

3.2 Future Schedule

Week	Sydney	Maram	Nikhil
09/27/21	Have a clear layout of the assembly of the design and assist with the first draft PCB schematic & board layout	Create a concrete first draft for PCB schematic design and send it to TA	Complete research on communication paths for remote configuration (panel->relay->microcontroller->server)
	Completed cost analysis	Have an approved/ nearly	Finalize wireless

10/04/21	with approval and ordered parts for the assembly of the project	approved PCB design, finalized schematic, finalized relay configuration	communication framework between external server and microcontroller
10/11/21	Gathering additional information on possible storage capability to document	Ordered all the parts for the PCB, awaiting for arrival	Finish coding out preliminary server-side framework; Do local testing within ECEB
10/18/21	Soldering top-layer PCB and observing any points of improvement; Determine measurement accuracy	Build PCB design and test for completion; Analyze board design to determine if version 2 of PCB is needed	Configure and code client-side framework on microcontroller; Integration testing with external server
10/25/21	Interface testing with the research panels per approval to determine how if/well our first-level design works; Individual readings of waveforms to determine possible rating spikes	Completed testing and finalized PCB design, if needed PCB v2 has passed audit and has been ordered, if not begin soldering components in preparation for interface testing	Complete wireless HTTP path between microcontroller and server; Begin working on configuration settings between relays and microcontroller
11/01/21	Isolating zones of our design to determine any alarming/unexpected characteristics on the PCB	Begin connecting interface functionalities to the PCB; Test wireless connection between panels and output results	Complete on-board setup for panel configuration; Begin connecting configuration capability with wireless network
11/08/21	Utilize lab equipment to determine any faults between the microcontroller or wireless communication	Finalize interface troubleshooting; Mount PCB board inside of Attabox; Begin configuring OLED and troubleshooting manual switches	Finalize wireless integration of server-board as well as board-panel communication; Begin working on wireless transfer of monitored panel data (4 key metrics)
11/15/21	May require a third PCB order for possible safety measures or points of improvement	Finalize OLED and manual switch analysis; Ensure functionality with the wireless network	Complete wireless network functionality including monitoring critical data; Set up web portal/GUI for project front-end
11/22/21	Testing to determine whether there is wireless communication capability between input readings of two or multiple solar panels	Mount attabox on the roof of ECEB to be permanently connected to solar panels; Test all functionalities to ensure completion.	Finish setting up external web-based portal; Finalize data visualization on portal; Complete verification of data reading across all points of communication
11/29/21*	Complete modular and integration testing; Demonstrate project working; Prepare project presentation	Complete modular and integration testing; Demonstrate project working; Prepare project presentation	Complete modular and integration testing; Demonstrate project working; Prepare project presentation
	Finalize presentation and	Finalize presentation and	Finalize presentation and

12/06/21*	present; Prepare and submit final paper	present; Prepare and submit final paper	present; Prepare and submit final paper

Table 3: Planned Schedule of Work (per teammate)

*Note: * towards the completion of our project, work will become more combined with respect to reports and demonstrations. Hence, the tasks of the last 2 weeks have been entered as the same.*

4 Ethics and Safety

4.1 Ethical Issues

- Project Issues:
  - Solar Energy should not contribute to net greenhouse gas emissions and exacerbate global climate change, and our peripheral device additions shouldn't affect this either
    - Fix: We are exploring potentially recharging the power supply to our interface box by diverting some of the cleanly-made solar energy
- General Solar Panel Issues:
  - Costs and benefits of Solar energy should be distributed in an equitable way by regulatory agencies
  - Solar Energy should be environmentally sustainable - the recycling of solar panels at the moment is a huge impediment to their overall sustainability [3]
  - The manufacture of solar panels has also seen negative outcry due to problems like forced labor camps for polysilicon [4]

4.2 Safety Concerns

- Arc Flashes - Flash Burn and Blast Hazards
- Electric Shock, with particular scrutiny on faulty wiring as well
- Falls - due to the location itself of the solar panels for this project (ECEB roof)
- Thermal Burn Hazards
- Over-current/voltage - ideally will be directly countered by our interface box

4.3 Safety and Regulatory Standards

4. IEEE Ethics Code #1: 'hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, and to disclose promptly factors that might endanger the public or the environment' [5]
5. IEEE Ethics Code #7: 'to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others' [5]
6. IEEE 1547-2018 - IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces [6]

7. NREL/TP-550-38603 October 2005: Procedure for Measuring and Reporting the Performance of Photovoltaic Systems in Buildings [7]

The following are standards and procedures we intend to follow when computing and collecting our measurements for our project. We plan to follow these guidelines carefully in order to keep ourselves and others safe.

5 Conclusion

Our final goal is to have an easy-to-use interface supported by our smart box that allows for accurate and convenient monitoring and up-keep of multiple ECEB research solar panels. We aim to have a prototype that can easily be scaled to meet the entire requirement of available solar panels, and in the end be successfully deployed in the ECEB!

5.1 Success Criteria

- With a focus on scaling up to meet the requirements of the solar panels available, we need to be able to interface with at least 10 research solar panels to be successful
- Interfacing with a solar panel successfully encompasses accurately monitoring its voltage, current, power output, and temperature while simultaneously reporting this data to an external server.
- Remote Wireless Access towards the panels for the authorized ECEB personnel will be successful when it allows for these personnel to configure the solar panels from an external system. A successful interface will also provide aesthetic visualizations of panel data for observation (and possibly for general viewing).
- A successful prototype will also maintain the ability to manually control the interface box with in-box buttons and switches as a fail-safe

6 References

[1] “Heartland 8 x 6 x 4 inches AH864C enclosure - Attabox: Non-metallic ENCLOSURES - polycarbonate and fiberglass,” *Attabox*, 15-Jun-2021. [Online]. Available: https://attabox.com/product/heartland-8-6-4-ah864c-enclosure/. [Accessed: 27-Sep-2021].

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