All-in-One Photovoltaic Sensor

DIVIDE & CONQUER 2.0

Senior Design I

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Customer and Sponsor: Orlando Utilities Commission (OUC)

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Project Narrative

As greenhouse gas emissions continue to rise on Earth today, one of the biggest challenges is to find new ways to produce clean energy reliably and efficiently. Many companies around the world have set a goal of reaching carbon neutrality to combat global warming. The Orlando Utilities Commission (OUC) is one of many companies which has established a similar goal; OUC's goal is to reach 50% carbon neutrality by 2030, and to reach 100% carbon neutrality by 2050. Our group has taken a part in OUC's objective to achieve sustainable energy production by developing data sensing equipment to pair with OUC's existing solar panel array.

The goal of our project is to develop a low-cost, all-in-one photovoltaic (PV) sensor device which will allow our customer, OUC, to gather data from their solar panel arrays. The all-in-one sensor will be able to collect voltage, current, temperature, and irradiance directly from the customer's solar panels. The data that our solution will provide the customer with includes numerous benefits. Firstly, through voltage and current values collected at each panel in an array will allow for technicians to detect a faulty panel in an easy-to-use manner. This solution would significantly reduce loss of power generation when a panel becomes faulty as this would reduce the time [and money] it would take for a technician to identify a faulty panel. Secondly, our solution will collect large amounts of granular data for OUC to generate accurate representations of temperature and irradiance at a solar panel array over a period, as well as energy collected over a period.

Our all-in-one PV sensor will function as a series of collector nodes, or microcontrollers, mounted onto each solar panel in an array. The collector nodes will be able to collect and wirelessly transmit multiple, granular pieces of data like voltage and current, temperature, and irradiance from the onboard DC optimizers, thermocouples, and pyrometers, respectively, to a receiver node. The receiver node will be able to compile collected data into a database, as well as display collected data in real-time. It is from our solution that OUC will be able to reach 50% carbon neutrality by 2030 and achieve 100% carbon neutrality by 2050 as our all-in-one PV sensor will have a robust design that will allow for scalability to be implemented into large solar farm arrays composed of hundreds of solar panels.

Market Analysis and Customer Needs

Getting the measurement of the Voltage, current, temperature, and radiance on an array of solar panels are important bits of information that can help deduce problems with panels; and even understand and find ways to improve performance of panels. OUC, knowing this, tried to implement methods to acquire these measurements, but unfortunately were unsuccessful at developing effective solutions to combat the issue. So, we would now look at some of the solutions they tried to develop to give us a better idea of how to approach the project.

OUC installed a Solar Edge DC Optimizers that modulated the output voltage of the solar panel, maintaining string voltage. The Optimizers continuously receive data from the panel regarding the DC data that outputs from the panel over time; wirelessly transmitting information to an inverter close by. Although this might have seemed like a solution, the data recorded by the optimizer could not actually be viewed by the company. OUC tried many methods to receive this data, even using python to access the information and requesting the data from Solar Edge directly, but none of their attempts proved any result. Even still, the optimizer would not help to find issues pertaining to certain panels that have malfunctioned, but would modulate DC voltage, producing less power than expect. As a result, OUC would not know which panel is not working; only having a general view on which array has a problem. So, we can see why the DC Optimizer could not provide a definite solution.

Understanding the problem this rose, Rubin York even began to implement a device that would send a warning if a panel started to malfunction, and not output the required power. He devised a system to record the amperage flow, by using a voltage divider, a buck converter, and a Broadcom ACHS-7122-000E sensor. This proved successful to a point, being able to capture the current flowing through the circuit; however, there appeared to be some amount of electrical noise in the reading. Also, Rubin still had to go to each panel to measure the performance of each panel. Knowing that his idea was possible, he assembled a senior design team to design a device that could get the readings stated above. The team used a Raspberry Pi, Banana Pi, and an Orange Pi as sensors. They also used different ICs to receive the desired information. Although they had a good attempt, the final product could only successfully record the voltage and irradiance.

We are now tasked with the same project. We are to design a device that can read and display the data of the voltage, current, temperature, and irradiance of an array of solar panels, measuring specific points on the panel. Our device would be able to identify problematic panels due to the readings and would be able to inform the company of the data collected. Thanks to the efforts of Rubin and our predecessors, we were able to get a clearer vision on how to approach the problem. So, now we would use the technology at hand, and any other electrical components to achieve the desired result we are required to produce.

External Market Analysis

Our team was unable to find any commercially available products that can sense voltage, current, temperature, and irradiance and possess the ability to transfer the data that it analyzes wirelessly to a local node or database. While that is the case, there is at least one working version of our sensor out there designed by Texas Instruments: the TIDA-00640. TI created this design for in-house testing purposes and does not offer this product commercially. This design featured a PCB that integrated voltage, current, and temperature sensors into a single system which was able to wirelessly communicate data to a central point through several wireless standards [TI Source].

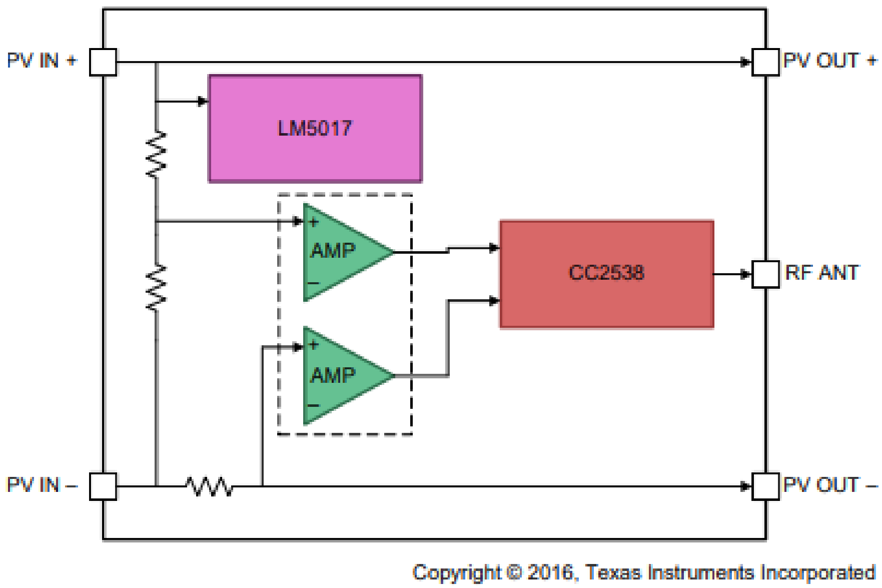

Figure 1: TIDA-00640 Block Diagram

The scope of the TIDA-00640's design is incredibly like our project as seen in Figure 1 and was the main driving point of inspiration for Phase 1 of the All-In-One PV Sensor. However, this design does not work directly with a Solar Panel but instead an MLPE, or Solar Module Level Power Electronic. While this is the case, their design would mostly work when connected directly to a Solar Panel's output via MC4 Connection Cables which was heavily incorporated by Phase 1's design.

Another design that was found during research was created by a team of researchers at Sandia national Laboratories in Albuquerque, New Mexico. [NM Source] They implemented a National Instruments Compact RIO model 9076 with an NI 9239 input module to acquire the voltage and current signals output by the Solar Panel at a rate of 2000 samples per second. However, it appears that this study was just to monitor the signals given off by the Solar Panel, not analyze and transmit these signals for later data analysis.

Ultimately, this endeavor to create a marketable All-In-One PV sensor to analyze and store panel-level data is a unique opportunity with very little competition. This will give way to unique and profitable solutions for the foreseeable future.

Constraints and Standards

In this project we are facing two major types of constraints: Constraints imposed by the customer/sponsor and engineering constraints which are standard requirements when designing. Because this project is directly sponsored by OUC, our customer, it is important that we prioritize customer constraints as we pursue our real design constraints to keep our funding.

Table 1: Constraints and Specifications

	Customer Constraint	Priority
1	Input voltage power supply 39V DC	High
2	Input power range 500 to 1200 W level	High
3	MC4 Standard connections	High
4	Removable device	High
5	Cost per sensor less than $20	Moderate
6	Accommodation terminal connectors 10 AWG wire	Low
7	Connection between DC Optimizers	High
8	Designing with thermocouple and pyranometer ports	Moderate
9	Sensor Durability lifetime more than a year	Low
10	Testing point time at least a week	Moderate
11	All other requirements standard	High
12	Sample rate should be 10-15 sec	Moderate

The constraints and requirements listed in Table 1 table above are those that are outlined by the customer as our product will be implemented into the customer's existing and functioning solar panel array. Each constraint has a respective priority.

Customer Constraints

Customer constraints are not necessarily required for the functionality of the device. These constraints exist to please the customer, given that this project may be marketed toward other existing businesses or continue to be used after we finish designing it. These constraints ensure that our completed design work toward the customer's expectations and specific situation:

- Ability to work directly connected to a Solar Panel via MC4 Connectors
- Less than or about $20 dollars per sensor, not including Thermocouple and Pyranometer sensors
- 'A-la-carte' external sensors/ability for the device to work without Thermocouple and Pyranometer sensors
- The PCB and its components must be powered by the Solar Panel's output and draw very little power as to not heavily impact the generation
- The All-In-One PV sensor must be able to wirelessly transmit measured data to a local collection node and store that data in a local, accessible database

These customer constraints create the issue that we aim to solve currently, an easily installed, marketable, and easily accessible option to measure the outputs of individual solar panels does not exist. Rubin York of OUC has reached out to our team to ensure that this prototype reaches reality and is able to be mass-produced for their personal use.

Engineering Constraints

Engineering constraints are required for our team to ensure that the All-In-One PV sensor that is created for this project can consistently operate in the field. While following the customer restraints, the following must be completed so that the design performs to the customer's expectations:

- Ability to withstand a maximum of 40V, DC and 10A, DC rated inputs
- Capable of measuring these rated inputs
- Ability to operate while missing temperature and irradiance circuitry
- A wireless communicator and wireless receiver to be implemented within range of each other
- Consistent and reliable data transfers from the sensors to the collector node
- The data read by the sensor must differ no greater than 5% from its original value
- The entire design must be enclosed within a weather-resistant container to prevent damage, and in the same vein, must be able to operate inside of this box with connections to the outside world
- Final design must be about $20 dollars per sensor to manufacture

IEEE 802 Standards

The IEEE (Institute of Electrical and Electronic Engineers) 802 Standards is a group of standards which encompasses various types of area networks like private area networks, local area networks, and metropolitan area networks. This family of standards is applicable to most, if not all wireless and wired data transmission methods people everywhere are familiar with.

In our project, we will be testing our product with three types of data transmission forms: ethernet, Wi-Fi, and Bluetooth. While we are planning to test our product with two types of wireless data transmission, Wi-Fi, and Bluetooth, we ultimately plan to keep only one of the two for our final design.

The Wi-Fi certification is contained within the IEEE 802.11 standard, a part of the IEEE 802 technical standards. It provides the framework for implementing wireless LAN technology and is the world's most widely used computer networking standard. This component serves as the main component for establishing a wireless network for various devices. There are also numerous protocols contained within the 802.11 standard. The ESP32 device we will be using for our product is capable of 3 different protocols of the 802.11 standard: 802.11b, 802.11g, 802.11n. Each protocol of 802.11 is a successive advancement of the 802.11 standard, in that successive protocols support faster data transfer rates to transmit more data quicker and wider bandwidths to lessen interference from other devices.

Bluetooth SIG Standards

The Bluetooth SIG (special interest group) standards is a set of standards or qualities a product must possess for a manufacturer to grant a Bluetooth designation to a product. Originally, Bluetooth was standardized by the IEEE as part of the 802 family of standards, specifically 802.15.1, but has since been discontinued.

The specific Bluetooth standard we will be using in our product is Bluetooth Smart 4.x, which is a part of its parent standard, Bluetooth 4.0. Its novel characteristic versus other protocols of Bluetooth is its low-energy consumption and considerable communication ability. This has led to adoption across countless computer devices on the market today like smart phones, laptops, desktops, and of course, microcontrollers like the ESP32 we will be using for our product.

Design Requirements

Table 2 summarizes the required specifications for this project. The accuracy of the sensor's measurements is incredibly important to maximize; without it, the readings from are sensor grow increasingly useless. This table notes the mixture between customer and engineering requirements that are requested by OUC and found by our team to ensure this project reaches its best state.

Table 2: Design Requirements

	Requirement	Specification
1	Power supply	Solar panel
2	Available input power	400 - 1500 watts
3	Supplied ADC	12ADC
4	Specific cost	<$20
5	Connection to Solar panels	MC4
6	Accurate Voltage Measuring	Within 5% of real value
7	Accurate Irradiance Measuring	Within 5% of real value
8	Accurate Temperature Measuring	Within 5% of real value
9	Accurate Current Measuring	Within 5% of real value
10	Wireless Data Transfer	Effective data transfer
11	Protective packaging	Harsh weather resistant

Another requirement that needs to be considered is the position of the device where it should be powered up from the solar panel which is supposed to provide a DC voltage. However, when a small piece of 20''X10'' board solar panel was test for linear voltage, the voltage wasn't clean enough to be considered as a DC voltage signal. For that, to capture a clean DC voltage we need to integrate in our design a Maximum Power Point Tracking (MPPT) solar charge controller device to have the proper DC power voltage for our power supply.

One of the appropriate MPPT charge controller we can use is the TIDA 010042 or TIDA 00120. As seen in Table 3 it can be used for 12-V, 24-V, and 48-V solar panels and has good characteristics such as its efficiency is about 96% for the 12-V system and 97% for the 24-V system. It has also a large range input voltage around 15 to 60 volts with a high rated output current of 20A. This is a flexible design and not big of size 130mmX82mmX38mm. This MPPT was developed in MSP430F5132 MCU and made for small and medium solar charger solutions.

Table 3. Key System Specifications

PARAMETER	SPECIFICATIONS	UNIT
Input panel voltage range	15-60	V
Battery nominal voltage	12, 24	V
Rated maximum current	20	A
MPPT efficiency	>96	%
Interleaved buck operating frequency	180	kHz

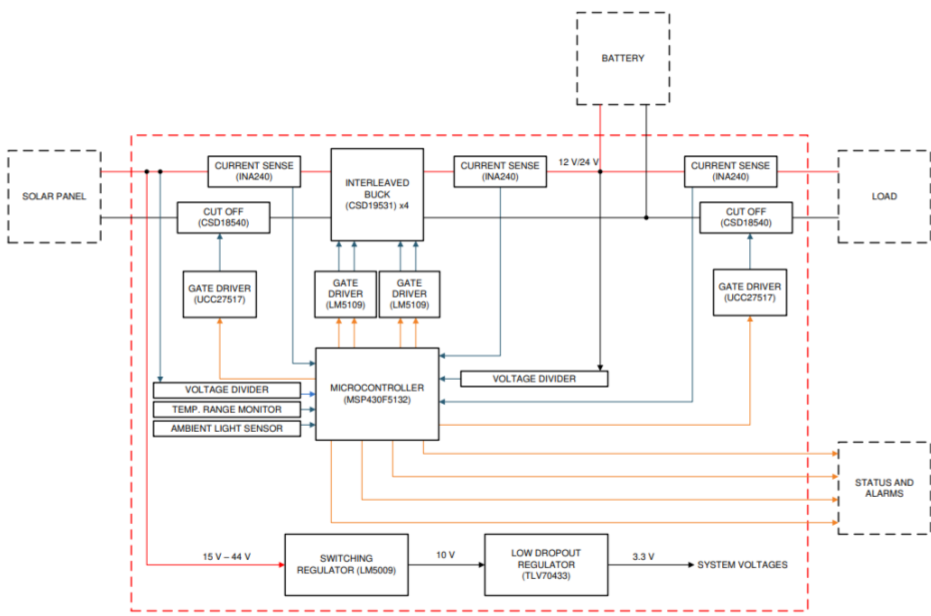

Figure 2. TIDA-010042 Block Diagram

It should be noted that the ultimate final design when mass-manufactured should be less than or about 20 dollars per sensor, not including the pyranometer and thermocouple. This goal may not be met while designing the product due to potential mistakes that the team may create or unforeseen damage the board and its components may receive. All other design requirements are planned to be pursued and met during the design and construction of the All-In-One PV Sensor as seen in Figure 2 Block Diagram.

Block Diagrams

Hardware Block Diagram

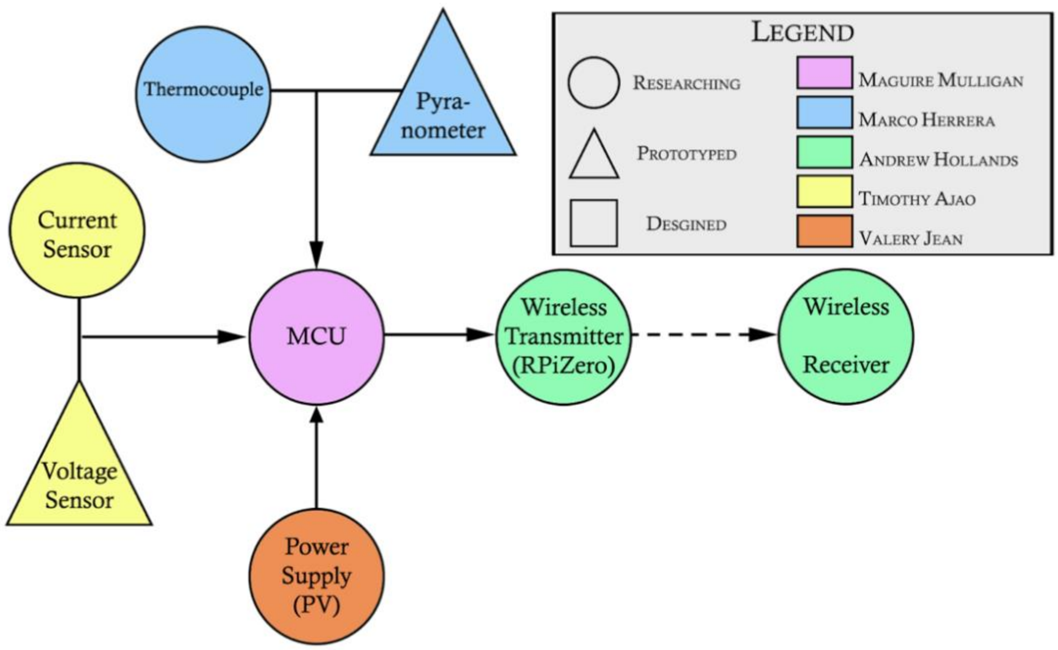

Figure 3: Hardware Block Diagram

This hardware block diagram, seen in Figure 3, displays the projected workload distribution among the group members. While a shape is filled with a specific color tying into a name, each shape has a secondary contact & researcher for that topic. For example, almost all coding-focused sections, such as the Wireless Transmitter and Receiver, are under one group member's name. Realistically, that member will be the main producer while others work alongside them to ensure success.

Sections of this hardware block diagram have been grouped to highlight where they will be coming from. For example, the Current and Voltage sensor will both be drawing their analysis from the DC output of the Solar Panel, and the Thermocouple and Pyranometer will be placed externally from the PCB and connected via wire. Therefore, these two groups have separate origins but similar destinations.

In early stages of research and development, it was believed that the Power Supply would be an external source. In furthering our research, it was identified that the sponsor OUC desired our board to be powered by the output of the Solar Panel to create a self-sufficient and auto-powered module. This has changed our budget on what we require in a Power Supply, but it still ultimately must be separate from the Current and Voltage sensor despite coming from the same source as it will not be measured.

Software Block Diagram

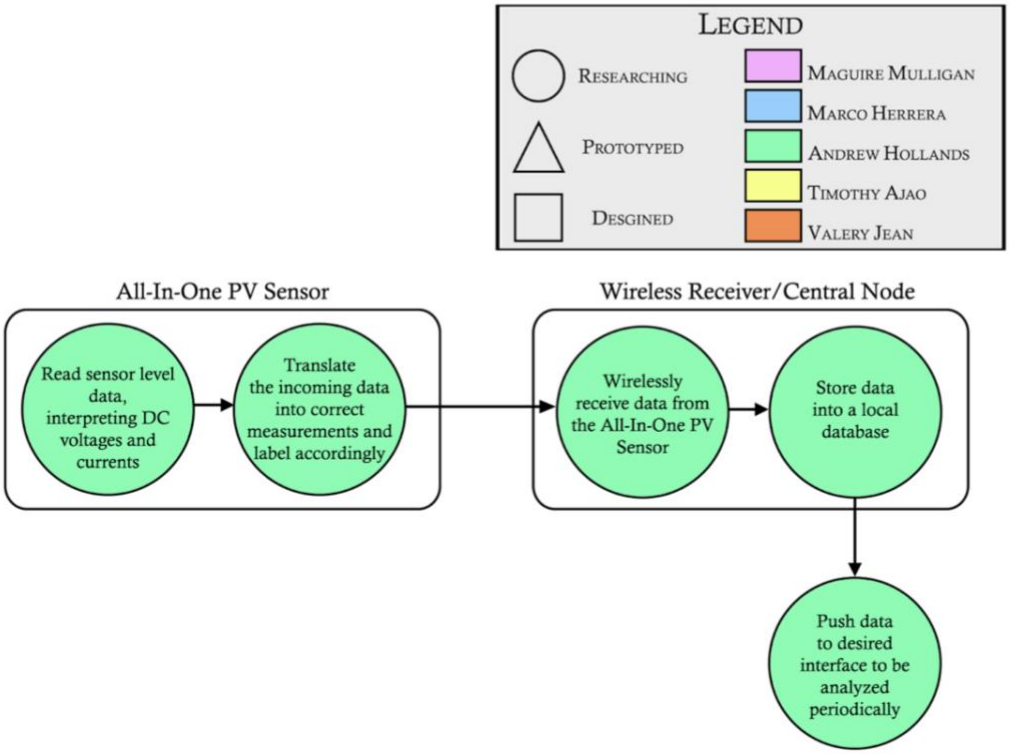

Figure 4: Software Block Diagram

The software block diagram in Figure 4 displays the projected workload of the wireless transmission and receiving of data. Again, as noted in the Hardware Block Diagram section, while the shapes are only one color, the entire team is participating in the research and creation of these sections alongside their main contact. Unlike the hardware block diagram, the software block diagram is grouped into two sections: the All-In-One PV Sensor and the Wireless Receiver/Central Node.

The All-In-One PV sensor includes everything on the lefthand side of the hardware block diagram, focusing on the reading and interpretations of the data that it gathers. The main software roadblock that is present in the All-In-One PV sensor is the translation of analog to digital via an ADC. Without this, the data would be unreadable in any useful format on the wireless receiving end. Based on the location of the input to the ADC, the data will be labelled and sent wirelessly to the central node.

The Central Node is where all the data is stored and where all the data will be accessed at future times. This is entirely separate from the All-In-One PV sensor and will be housed away from the Solar Panels, connected directly into the network at OUC. Data will be wirelessly received, sorted, stored, and pushed to a local database for future reference.

Prototype Illustration

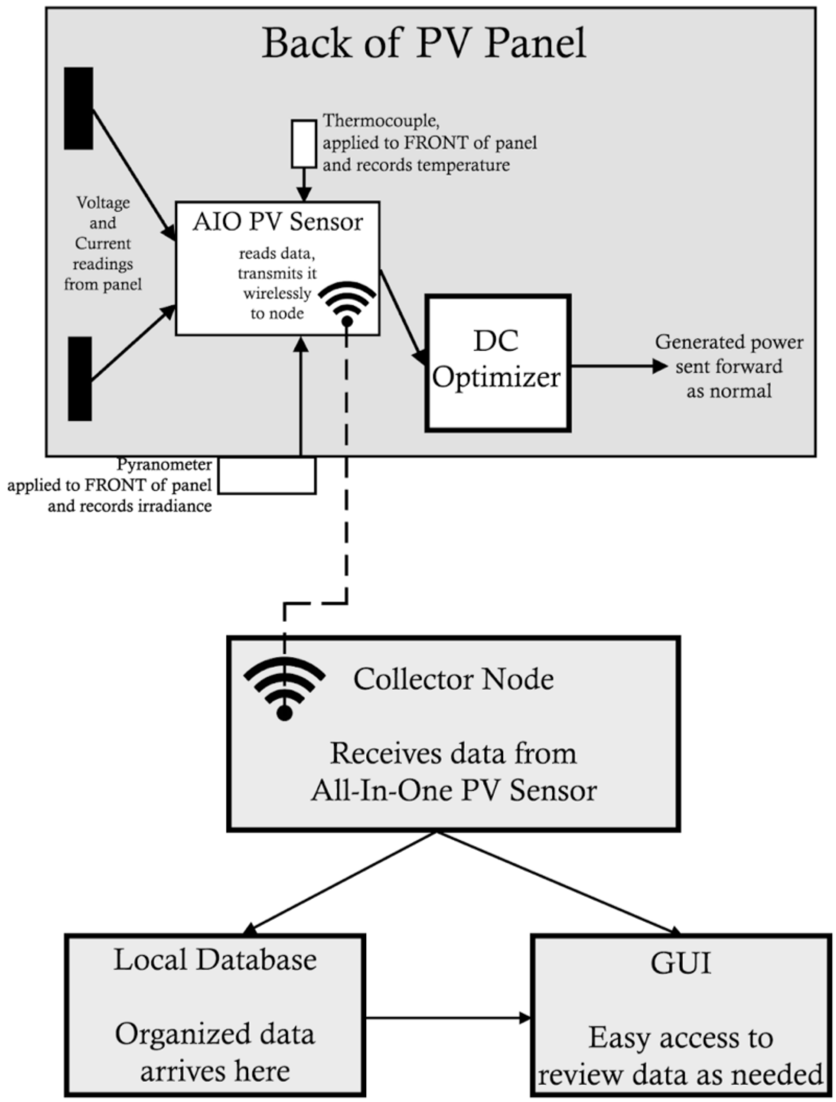

Figure 5: Prototype Design

Our prototype illustration in Figure 5 aims to explain the order and location for all the components in the entire project's scope. From the figure, the All-In-One PV Sensor, shortened to AIO PV Sensor, takes two inputs directly from the panel and an additional two from sensors placed directly on or adjacent to the panel. The AIO PV Sensor will be placed in series between the panel's generation and a DC Optimizer (outside of this projects scope and provided by OUC for each panel) ideally making very little to no alterations to the generated power.

From the AIO PV Sensor, the data is wirelessly transmitted to a Collector Node, ideally about 10 to 20 meters away from the sensor. This data will be sent to a local database and a relatively simple GUI may be developed for a customer to review the generation parameters.

House of Quality

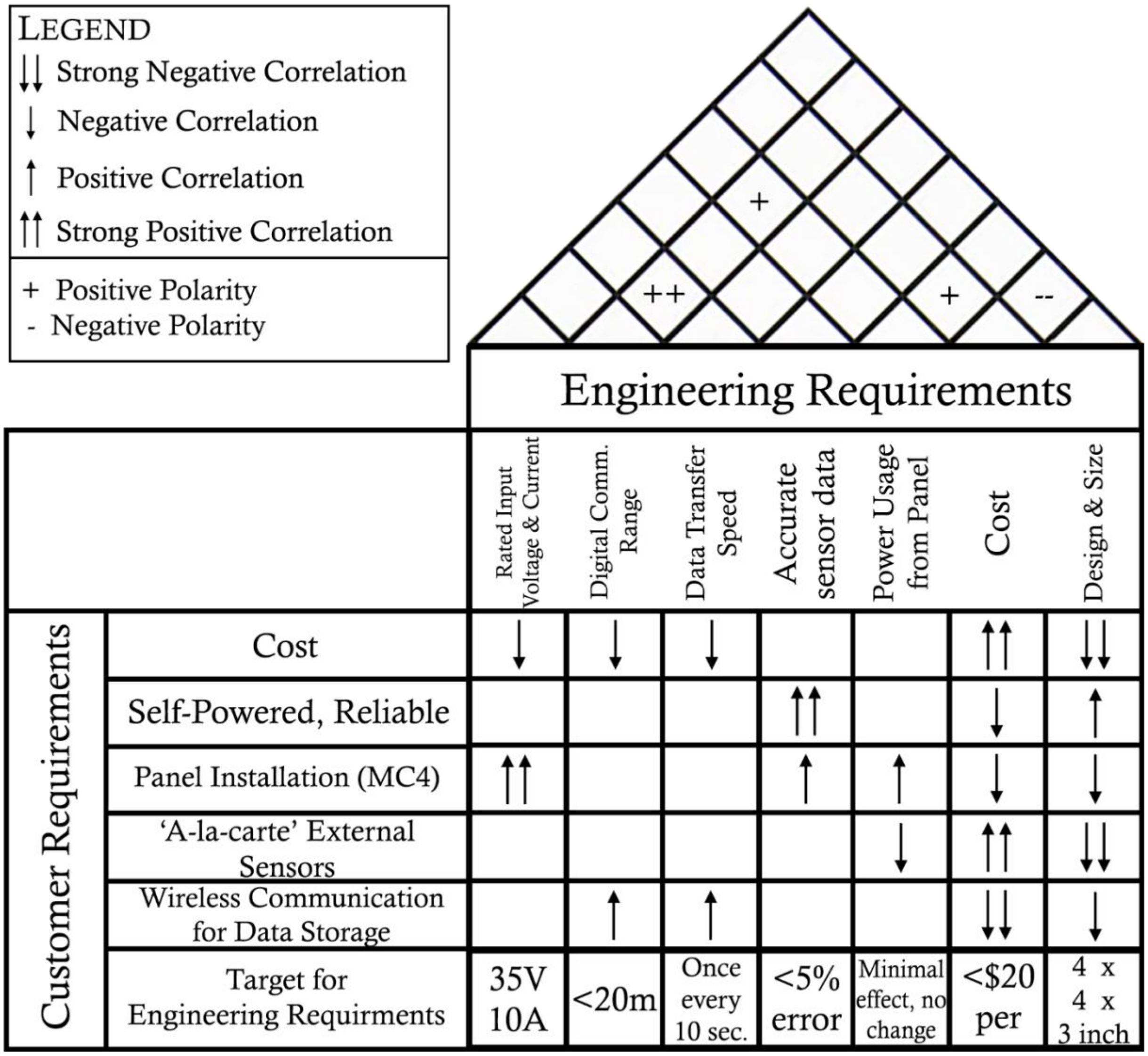

Figure 6: House of Quality

Our created House of Quality matrix seen in Figure 6 can summarize the customer's requirements compared to the engineering specifications that our team was given to follow. What the customer heavily prioritizes is the ability to have 'A-la-carte' external sensors, meaning that the pyranometer and thermocouple sensors, capable of measuring irradiance and panel temperature respectively, should not be a required component of the sensor. All sensors are expected to be able to measure a rated voltage and current and send that data wirelessly to a local collector node.

Given that the cost is also a priority for the customer, this 'A-la-carte' choice allows the individual cost of a sensor to be lower than average as only one of three produced sensors for this project will make use of a pyranometer and thermocouple.

Budget

As on both *Table 4: Initial Project Budget for Redesigning Phase I* and *Table 5: Initial Project Budget New Design* some of the components for this project have an inflated price due to the distribution problems and semiconductor backlogs leading to shortage in chips. To bypass some of these limitations we be using third-party sellers for some the hardware such as the ESP32 and Raspberry Pi 4 sold in Amazon to guarantee a timely delivery.

In addition, both tables' costs should not be taken as a final amount since some of our initial parts would most likely be out of stock, in back order or the part we thought it would best fit our design did not fully meet our criteria. As seen below on *Table 4: Initial Project Budget for Redesigning Phase I* is the previous teams main material cost which have already exceeded our overall initial budget. This is one of our client constraints which is making a low-cost PCB 'All in One PV Sensor', thus we need to monitor and decided which parts are most cost effective to us in our design without compromising quality and reliability.

Table 4: Initial Project Budget for Redesigning Phase I

	Component Description	Vendor	Unit Price	Quantity	Total Price
1	Raspberry Pi 4 Model B 2019 Quad Core 64 Bit WiFi Bluetooth (4GB)	Amazon	$134.99	1	$134.99
2	SP-110-SS: Self-Powered Pyranometer	Apogee Instruments/ Part provided by OUC	$223.00	1	$223.00
3	Thermocouple Probes with Lead Wire & Molded Transition	Omega/ Part Provided by OUC	$30.42	2	$60.84
4	Raspberry Pi Zero 2 W (Wireless / Bluetooth)	Amazon	$49.99	3	$149.97
5	PCB	To be determine	$30	3	$30
6	Weatherproof Enclosure	Weatherproof cases	$100	1	$100
Total Estimated Cost:					$698.80

Table 5: Initial Project Budget New Design Phase II

	Component Description	Vendor	Unit Price	Quantity	Total Price
Wireless Transmission and Data Storage					
1	ESP-32S Development Board 2.4GHz Dual-Mode Wi-Fi	Amazon	$10.99	6	$65.94
2	Raspberry Pi 4 Model B 2019 Quad Core 64 Bit WiFi Bluetooth (4GB)	Amazon	$134.99	1	$134.99
3	SAMSUNG 128GB EVO Plus Class 10 Micro SDXC	Amazon	$19.10	1	$19.10
Sensors					
5	SP-110-SS: Self-Powered Pyranometer	Apogee Instruments/ Part provided by OUC	$223.00	1	$223.00
6	Thermocouple Probes with Lead Wire & Molded Transition	Omega/ Part Provided by OUC	$30.42	1	$30.42
7	Current Sensor	To be determined	$6	1	$6
	Voltage Sensor	To be determined	$5	1	$5
Power supply for 'All in One Sensor'					
	MPPT Charge Controller	To be determine	$23.99	1	$23.99
Total Estimated Cost:					$508.44

In *Table 5: Initial Project Budget New Design Phase II* we can see the breakdown of the major components of our new design and the cost associate with them. Since this is a work in progress currently most of the secondary components still don't have a stable price range as we are yet to determine an exact price for a PCB. As seen in *Table 5: Initial Project Budget New Design Phase II* we decided to us ESP32 instead of a raspberry pi zero since the ESP32 has an analog to digital converter already integrated making more cost effective.

Project Milestones

Table 6: Senior Design I Milestones

Number	Milestone	Tasked	Start Date	End Date	Status
Introduction to Project					
1	Meet the team, advisors, and customer	Group 6	1/11/2022	1/17/2022	Completed
2	Familiarize with the project	Group 6	1/17/2022	1/25/2022	Completed
3	Scout the location for implementation	Group 6	1/25/2022	1/27/2022	Completed
4	Role Assignments with tech advisor	Group 6	1/25/2022	1/28/2022	Completed
5	Part Identification and Classification	Group 6	1/27/2022	2/4/2022	In-Progress
Project Documentation					
6	Initial Project Document	Group 6	1/24/2022	2/4/2022	Completed
7	Updated Divide and Conquer Doc.	Group 6	2/12/2022	2/18/2022	Completed
8	First Draft Senior Design I	Group 6	2/14/2022	3/25/2022	In-Progress
9	Second Draft Senior Design I Rev.	Group 6	3/28/2022	4/8/2022	Pending
10	Final Report	Group 6	4/11/2022	4/26/2022	Pending
Research and Development					
11	Thermocouple and Hall-Effect Sensors	Marco	1/28/2022	2/18/2022	Completed
12	Node/MCU and Communication	Andrew	1/28/2022	2/18/2022	Completed
13	Node/MCU and Pyranometer	Maguire	1/28/2022	2/18/2022	Completed
14	Power and Hall-Effect Sensor	Timothy	1/28/2022	2/18/2022	Completed
15	Power and Voltage Sensor	Valery	1/28/2022	2/18/2022	Completed
16	Filtering Circuit and Amplification	Group 6	2/4/2022	2/18/2022	Completed
17	Board Prototyping V1&V2	Group 6	2/21/2022	3/28/2022	Pending
18	Final Prototypes Stress Tests	Group 6	3/14/2022	5/3/2022	Pending
19	PCB Layout	Group 6	3/28/2022	5/3/2022	Pending

Table 7: Senior Design II Milestones

Number	Milestone	Tasked	Start Date	End Date	Status
1	Working PCB V1 Stress Test	Group 6	4/27/2022	5/30/2022	Pending
2	Final PCB Stress Test	Group 6	5/16/2022	7/4/2022	Pending
3	All in Once PV Sensor	Group 6	5/16/2022	7/18/2022	Pending
4	Conference Paper	Group 6	5/16/2022	7/26/2022	Pending
5	Design Demonstration	Group 6	5/26/2022	7/26/2022	Pending

As seen above on *Table 6: Senior Design I Milestones* our team designated specific target dates to stay within a set schedule and design certain aspects of the 'All in One PV Sensor'. This was carefully selected to have a certain level of control of our workload and do not have setbacks due to lack of organization within the team. To further explain the breakdown for *Table 6: Senior Design I Milestones* in the first part of the section we can see the introductory part of the projects where we assign specific dates to become familiarized with the team and the project itself. On the second part of *Table 6*, we itemized the range of dates where we are task to provide documentation need to be submitted for the Senior Design advisors to provide feedback and monitor our progress.

The final part of *Table 6* is the dates designated for the research and development of the 'All in One PV Sensor'. These dates are categorized by date and individual point of research to further break down the design workload. In addition to these dates, we also included a section on *Table 6* where we selected a range of reasonable dates for our first working prototype, prototype stress test and the first stage for PCB layout these dates also serve as progress markers targeted to the OUC sponsor for them to have a clear timeline of our design process.

On *Table 7: Senior Design II Milestones* we identified possible dates for our final paper presentation and conference paper to have a clearer picture of future dates to look out for to adjust our workload according to these dates. Furthermore, we also predict the final stage dates where our final PCB design would be built and when will be stress tested.

Resources

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II. “ESP32 Technical Reference Manual,” Espressif Systems. https://www.espressif.com/sites/default/files/documentation/esp32_technical_reference_manual_en.pdf

III. “IEEE Standard for Local and Metropolitan Area Networks: Overview and Architecture,” IEEE.
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V. “Omega Sensors,” Omega Engineering Inc.
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