All-in-One Photovoltaic Sensor

Senior Design I

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Sponsored by the Orlando Utilities Commission

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1. Executive Summary

There exists a great push toward renewable energy on almost every front of the world's improvement. As time goes on, and the world continues with their journey to become completely carbon-neutral and embrace the wonders of renewable energy, people begin to question just how reliable this renewable energy is. One common doubt is the reliability of the renewable sources that depend on the weather, such as solar panels. As solar panels become more and more commonplace, it becomes that much more important to describe and highlight how it performs throughout the day. Without reliable measurement and an easy way to access these measurements, solar panels become a black box of energy generation that an average consumer cannot predict or depend on blindly. Moreover, how can the engineers and workers understand how a solar panel is performing without having a method to measure that performance? If a solar panel could come with a pre-installed sensor that can measure its outputs and surrounding environment, then maintenance and installation become a much clearer experience.

This project, bestowed upon us by the Orlando Utilities Commission via Rubin York, aims to combat that exact issue. Oftentimes, solar panels fail. It is expected that they will, just as all other means of power generation may in their lifetimes. When a system that contains a single solar panel fails, it is easy to understand; that solar panel begins producing at a much lower rate, and a consumer can instantly tell that their solar panel is malfunctioning. However, solar panels are commonly installed in arrays. When a single solar panel fails inside of an array, the generation of the entire array is greatly affected, and it is impossible to determine which solar panel has failed without testing each solar panel individually. This creates an extremely large workload for any engineers attempting to rectify the failed solar panel and can greatly limit power generation for days.

Implementing a sensor that can measure a solar panel's output in volts and amps, and its surrounding temperature and irradiance can greatly reduce the time it takes to pinpoint a panel that has failed and, in the best case, eliminate that time if a sensor is placed on every panel. This is what the All-In-One PV Sensor aims to be: A simple-to-install, small and cheap sensor that can attach directly between a solar panel's output and the grid that can measure a solar panel's voltage, current, temperature, and irradiance exposure, and communicate that data to a local database for analysis.

The All-In-One PV sensor will use a simple voltage divider and shunt resistor to measure the panel's output voltage and current respectively. The sensor will also optionally employ a thermocouple and/or a pyranometer, allowing the All-In-One PV Sensor to operate with or without the thermocouple and pyranometer. This will greatly reduce the cost of the average sensor, as the average irradiance and temperature of panels directly next to each other will be about the same. Therefore, a fully constructed model will feature voltage, current, temperature, and irradiance measurement, while a minimally constructed model will only feature voltage and current measurement. Both models will be completely functional and fully able to communicate this data to a local database to be stored.

This paper documents the All-In-One PV Sensor's design process. An initial overview of the project's scope is given, followed by an in-depth look into the surrounding technology that relates to our All-In-One PV Sensor and the components that will be used inside of it. The components will be greatly analyzed and brought down to a single, working design, and that design will be tested rigorously and described. Finally, this paper features the administrative details of the All-In-One PV Sensor's creation, touching on its milestones and budget. An appendix is attached at the end detailing the use of copyright materials and our references.

2. PROJECT NARRATIVE

In the Project Narrative, the background of the project is explained alongside the current objectives and requirements set forth by our customer and sponsor, the Orlando Utilities Commission (OUC). Tables listing the various specifications and constraints that limit the functionalities of our product are explained in the Project Requirements and showcased in the Initial Diagrams. These goals and guidelines help establish a sense of direction and the required physical and virtual quantities that can allow us to complete this project to scope.

2.1 PROJECT BACKGROUND

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. We will be completing phase II of this project, emphasizing on what was not completed in phase I. Phase I completion includes functioning voltage- and temperature-sensing components, lacking current- and irradiance-sensing components.

2.2 PROJECT OBJECTIVES

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.

2.3 PROJECT REQUIREMENTS

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 a much larger solar panel array.

2.4 INITIAL DIAGRAMS & VISUALIZED PROTOTYPES

Tables 2.1 and 2.2 showcase the specifications and some of the constraints that we will face while developing this project, respectively.

Table 2.1 Specifications

	Requirement	Specification
1	Power supply	Solar panel
2	Available input power	1500 watts
3	Sample rate	10-15 seconds
4	Specific cost	<$20
5	Connection to Solar panels	MC4
6	Accurate Voltage Measuring	Moderate Priority
7	Accurate Radiance Measuring	Moderate Priority
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

Table 2.2 Constraints and Specifications

	Requirement	Specification
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

The following figures, Figure 2.1 and Figure 2.2, showcase a block-diagram representation of our project's layout and scope. With this, we aim to understand how the All-In-One PV sensor will connect within itself and ultimately extend outward virtually, communicating the recorded data over a local network so that it can be stored.

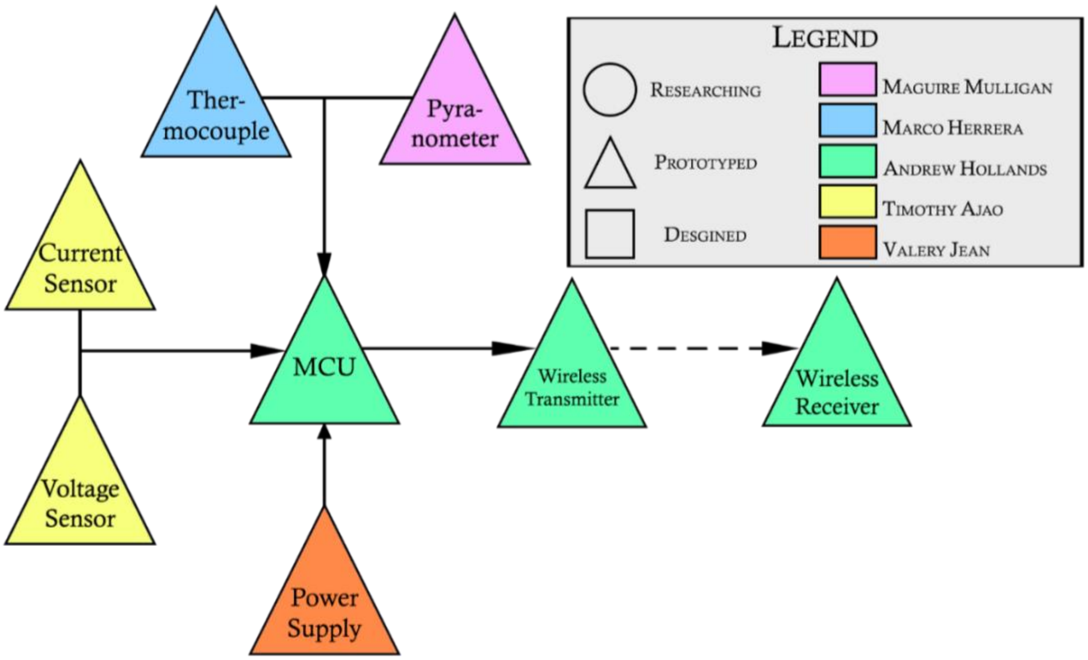

Figure. 2.1. Hardware Block Diagram

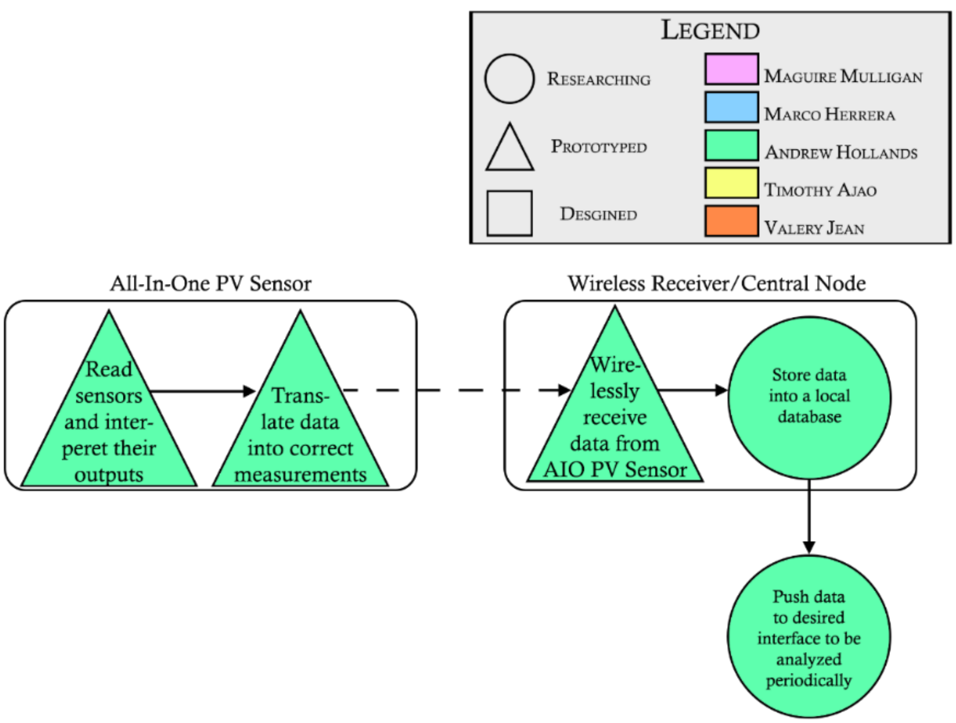

Figure 2.2: Software Block Diagram

Our final diagram is the overall prototype design, not considering the inner workings of the All-In-One PV Sensor. This diagram, seen in Figure 2.3, shows how the sensor will connect on to a standard solar panel at the Pershing Research Array provided by OUC, being placed in series between the Solar Panel's output and the DC optimizer that cleans the generated power and sends it toward the grid. The All-In-One PV Sensor will be able to wirelessly communicate data to a local collector node such that the data can be stored and viewed at a local machine for data analysis.

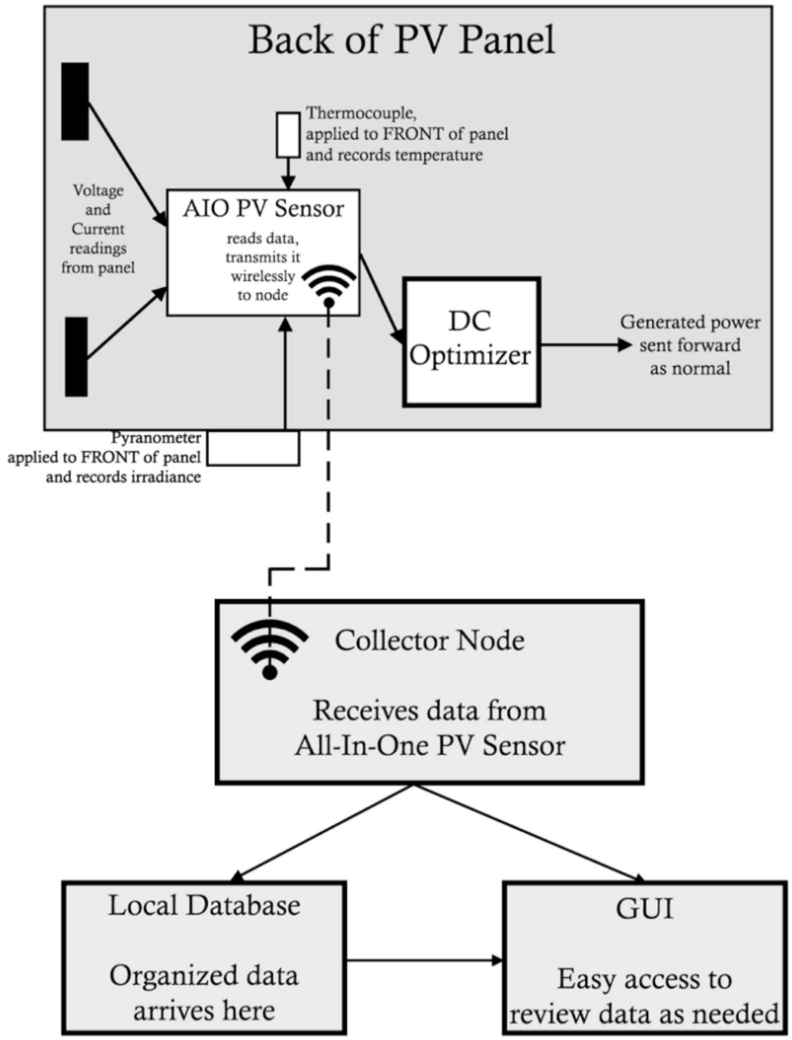

Figure 2.31. Prototype Design

3. CONSTRAINTS AND STANDARDS

When it comes to make a new product specially a new technology, constraints, and standards play an important role in designing. Constraints are all special requirements that might be imposed by a customer, environment, or other factors and can affect the design limitation. Standards are all the requirements that design should follow to be considered as a standard product in order to work with other standard products. All Standard characterizations have been described in a formal document in order to define a standard product. In All-In-One PV sensor, we are committed to comply with the IEEE and organizations' standard requirements for our design.

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.

3.1 CUSTOMER CONSTRAINTS

Connectors

For our power connection, there two types of connectors that need to be considered the MC4 connector that will come from the solar panels and the terminal blocks that will be on our PCB.

MC4 Connector

MC4 connectors, this is where our device will be powered up and they are also a type of connection that is required by the customer/sponsor (OUC). Our device should follow this requirement as another constraint. MC4 is defined as multi-Contact and 4 is for the 4mm contact pin. This type of connection is easy to connect by hand but almost impossible to disconnect the same way. This is due the safety just to avoid any accidental disconnection when the system is loaded.

The newest model of MC4 PV connectors, the MC4-Evo2, was made with the highest performances to comply with the worldwide certifications and the market by giving the reliability of benefits for years expertise and the standardization for a large range of connection. The figure below shows the newest version of MC4 it is MC4-Evo2 male and female. They come with a wide range of cable cross-sections from 2.5 mm2 to 10mm2 for range of wire gauges of 8 AWG to 14 AWG. Therefore, the cable of 6mm2 cross-section is associated with the 10 AWG that is required for the project. Figure 3.1 displays these connecting cables.

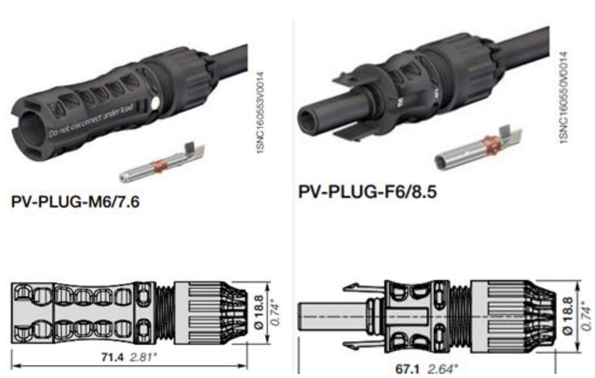

Figure 3.1. Female and Male MC4 Connectors, respectively

Terminal Blocks

By keeping everything standard, it comes to mind to find what type of connectors that we need to make our design running smoothly. Because it is important that we must comply with the customer requirements, and we cannot change any parameters that he has requested. It is necessary for us to use the proper wires and connectors regarding the input voltage that will be across the PCB and how many connectors that will be needed. From this view, we analyze that according to the requirements of OUC and design standards, we will have two inputs coming from the solar system and in the same way two outputs that going to the DC optimizer because both input and output are carrying two wires each. A clear description of the design will be showing when we are going to test the device.

In addition, we will need to connect other components like the thermocouple and the pyranometer. Those circuits will require each an additional terminal block. For those connections, they use a single wire for their polarity unlike the MC4 cable using two for a unique pole. That means each device will use one terminal block. Therefore, our PCB will carry four terminal blocks in which there will be eight connections.

The terminal block showing below is the one that will be connected to the PCB to provide energy to the power supply. The terminal block is made to carry a range of 10 - 26 AWG that is coming from the solar panels and can go up to 300V with a maximum current of 30A. This is the TB005-762 model. This model was made with steel-zinc plated screw -rising cage clamp. It has been provided by the customer (OUC) to us. Figure 3.2 displays these terminal blocks.

Figure 3.2. 10-AWG and 16-AWG terminal blocks

3.2 ENGINEERING CONSTRAINTS

Engineering constraints are constraints that limit the creation of our device in ways that customer constraints do not. These types of constraints ensure that the All-In-One PV Sensor will consistently operate in the field all while operating as intended, following standards and codes.

The final PCB must be able to withstand a maximum of 40 V DC and 10 A DC and it must also be capable of measuring these inputs using components that are directly on the board. Along with this, it must be able to operate 'a-la-carte', meaning that the board should be fully functional when the temperature and irradiance sensors are not connected to the board. The All-In-One PV sensor must be able to record its measurements and transmit those measurements wirelessly to a local node database and have the values transmitted be no greater than +/- 5% of its original value. The entire design must also be capable of working from the inside of an enclosure such that it can operate in intense weather conditions without having the life or longevity of the device threatened.

3.3 Other Related Standards

Pyranometer Standards & Specifications

Pyranometers come in several classes that must be considered: Classes A, B, and C which are subject to classification according to ISO 9060:2018. [3.1] These classes are summarized in Table 3.1. Because the price can be seen to be comparatively high in Classes A and B, a Class C pyranometer will most likely be selected for this project as the accuracy and response time of the pyranometer are not of high importance.

Table 3.1 Summary of ISO 9060:2018 Pyranometer Classes [3.2]

Class	A	B	C
Accuracy	High	Good	Moderate
Response Time	< 15 seconds	< 30 seconds	< 60 seconds
Smallest Detectible Change	1 W per square meter	5 W per square meter	10 W per square meter
Error	Negligible	± 1%	± 2%
Comparative Price	4x the cost of Class C	2x the cost of Class C	-

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.

4. RESEARCH

Before the team can create a functioning prototype and move forward with a final design, research into each part must be done. In this section, relevant technologies and existing efforts in the market will be analyzed such that the team understands the components that will surround the All-In-One PV Sensor. Following this, an extensive look into core components is done so that the team can move forward with creating the All-In-One PV Sensor.

4.1 RELEVANT TECHNOLOGIES

While we are developing our own PCB, we will also be implementing existing, popular hardware available on the market that will largely assist in organizing and transmitting our collected and filtered data. In this section, we will discuss general technologies associated with the hardware we will be implementing as well as actual chips that support wireless communication methods mentioned earlier in this document. Due to the nature of this project's existence, this sensor will be placed at the Orlando Utility Commission's Research Array and therefore it is important to understand how their arrays function. To do this, the functionalities of several out-of-scope technologies will be analyzed.

4.1.1 SOLAR ARRAYS

A solar cell panel, also known as a solar electric panel, is an assembly that consists of photo-voltaic cells. These cells convert sunlight into electricity by producing a current. A system of solar panels is also called an array. Using light energy from the Sun, solar panels convert the solar radiation into electricity. Most of the time, the cells used in these modules are thin-film or crystalline silicon.

Most solar panels are made of rigid materials, while semi-flexible ones are also available. The cells are connected in series to increase their current and voltage. Although the manufacturing process of solar panels is standardized, the actual operating conditions of the components are not always known. A solar panel's output interface is usually located on the back of the panel.

The panels are also made of metal components such as racks and troughs. They can also be connected to a standard power supply using a USB interface. Although a single solar panel can produce a limited amount of power, most installations have multiple modules that can add additional current or voltage to the system. These components include an inverter, a battery pack, and a circuit breaker. A good solar panel installation involves carefully selecting the equipment that will help maximize its output and minimize its energy loss.

Several companies are now incorporating electronic components into the modules to enable them to perform various tasks such as monitoring and fault detection. These include MPPT and power optimizers. In 2010, electronic components were also introduced that can compensate for the effects of shading, which can reduce the electrical output of multiple strings of cells in a module.

Conducting wires are used to make connections between the modules. Each panel is typically connected in series to form strings to output a desired voltage. These components can be paralleled to provide the ideal current capability for the system. These components can be used in parallel or series connections to allow current to bypass the modules that have high resistance. They can also prevent short circuiting of other strings.

Currently, most solar modules are produced using monocrystalline and multi-crystalline silicon cells. In 2013, the production of solar panels was dominated using crystalline silicon. Compared to other solar technologies, high-efficiency cells are more cost-effective. They are also used in space applications to provide the highest efficiency. Compound semiconductors known as MJ-cells are also being used in various solar technologies. One of these is concentrator photovoltaics. In rigid thin-film modules, the cells are produced on the same production line. The electrical connections are then made using in situ connections. The main types of cells used in this category are a-Si, a-Si+uc-Si, and a-Si tandem. They are produced using the same production line. If the substrate is an insulator, then monolithic integration can be done. The cells are then assembled into modules by bonding them to a transparent film and a polymer for bonding.

4.1.2 DC OPTIMIZERS

Our project requires lot of attention to what has been existed and why the Utility Commission needs us to come with as a new device. Despite the essential potentiality of the DC optimizer and the function that it plays in the system, OUC still requires something on the side to work with not a replacement for the DC optimizers, but something additional so he can do more analysis regarding the solar system and/or any single solar panel performance.

Because those solar arrays are set in series, any malfunctioning of any panel will affect the whole system and create a deficient performance. During a day, all areas are not covering with sun at the same intensity which can create a deficiency in one or more solar panel(s) in an array. There are several factors that can drive the system to low performance such as partially shaded conditions, multiple orientations of the sun and more. DC optimizer is a great technology that was made to encounter specially those situations. It is to optimize electricity generated by the solar arrays. When the solar panels are in contact with the sunlight, they generate DC voltage which will be converted to generate AC voltage.

DC optimizer tracks the voltage across each panel and maximize it by using a technology called MPPT (Maximum Power Point Tracker) technology before sending the right voltage to what we consider as an inverter meaning that the device that served to convert DC power of the solar panels to AC power that will be used by customers. On the other hand, our All-In-One PV sensors will in separate way by providing more data on each panel whenever it has needed. In other words, DC Optimizer can regulate the performance of the solar string up to 25% from the normal performance of the system whereas our device can give more information to do deep analysis. Figure 4.1 displays a typical DC optimizer configuration in relation to its surroundings, and Figure 4.2 shows OUC's DC optimizer configuration placed directly on its generating panels.

Figure 4.1. Typical DC Optimizer Configuration

Figure 4.2. OUC's DC Optimizer Configuration

4.1.3 INTERNET OF THINGS

The Internet of Things (IoT) is a broad term that refers to the interconnected world of physical objects that are embedded with sensors and other technologies that can exchange data with each other and with systems over the Internet. Although connected devices do not need to be on the public internet to be Internet of things, they do need to be able to be individually addressable. The concept of the Internet of Things is a broad range of technologies that enable the connectivity of various things, such as home automation and security systems. Most commonly, these include devices and appliances that are connected to one or more common ecosystems.

The IoT is being widely used in healthcare systems. There are various concerns about the security and privacy of this technology, and various regulatory and industry initiatives have been launched to address these concerns. Many energy-consuming devices such as lights, pumps, and household appliances have already integrated Internet connectivity. This allows them to communicate with utilities and manage their energy consumption more effectively. These devices can also be controlled remotely using a central management interface.

The smart grid is a utility-side application that uses the Internet to collect and manage energy-related data. This system helps utilities improve the efficiency of their electricity distribution and production. Aside from monitoring electricity consumption, it also helps protect the environment by monitoring air quality and soil conditions. Developing the right connectivity for resource-constrained devices can help improve the efficiency of emergency services. The standardization of the Internet of Things is expected to greatly benefit wireless sensing. This is evidenced by the number of Living Labs, which are organizations that are focused on collaborating and sharing knowledge to develop new products.

Cities can also benefit from the implementation of the Internet of Things through the provision of incentives. This can help them improve the efficiency of their operations and reduce their costs. The Philippines' favorable policies and favorable conditions make it an attractive place for start-up companies and multinational companies to establish their operations. The relationship between the developers and the governments that manage the city's assets is very important to the success of the Internet of Things.

The concept of the Internet of Things is divided into three phases: Tier 1, Devices, Tier 2, and the Cloud. The devices that are connected to the Edge Gateway are typically those that use a variety of protocols. The

Edge Gateway layer is a part of the data aggregation system that's used to collect and secure the data from various sensors. It provides various features such as pre-processing the data, establishing a secure connection to the cloud, and monitoring the devices. The final tier includes the cloud-based apps that are built for the Internet of Things. These apps are typically polyglot and are secure using HTTP/OAuth.

The cloud tier of the Internet of Things system is typically composed of event-based messaging and networking systems. Some experts classify it as the platform, edge, or enterprise tier. The web of things is a part of the system that's focused on the convergence of data collected by sensors and web applications.

The goal of the Internet of Things is to control the flow of information between the various connected devices. This is done using process management techniques. The scalability of the network space is very important for the success of the Internet of Things. With the number of devices expected to grow significantly, the IETF's 6LoWPAN would be used to handle the influx of data. The processing power of the edge devices is typically limited. This limitation makes it difficult for them to process and analyze data collected by the sensors. An average illustration of IoT is shown in Figure 4.3.

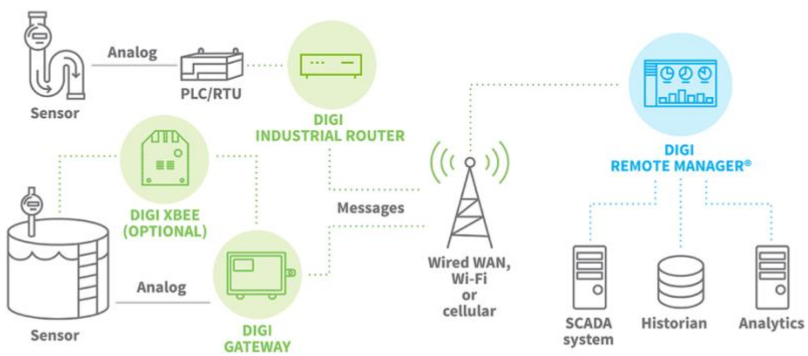

Figure 4.3. IoT Diagram

4.1.4 System on a Chip

System-on-a-chip, or SoC, is a prevalent technology we will be implementing in our design in both our PCB and accompanying Raspberry Pi 4 microprocessor. SoC refers to a processing unit which is composed of a single unit which at one point used to be composed of multiple units. For example, a computer 20 years ago would have a motherboard with multiple separate components soldered onto it like a CPU, memory, storage, GPU, and numerous busses to connect the components. Today, a SoC is a combination of all the previously listed components, miniaturized into something as small as a Washington quarter.

A system on a chip is a complete electronic package that consists of various computer components. It can be used to implement various electronic functions. System on a chip usually consists of a central processing unit (CPU), graphics processing unit (GPU), and system memory. A SoC is designed to meet the requirements of incorporating multiple computer components onto a single chip. Instead of having multiple components assembled onto a circuit board, an SoC simplifies the process by creating one unit of electronic circuits. There are many types of SoCs, such as general-purpose CPUs and specialized circuits that handle various special-purpose tasks. Some of these include tasks related to image processing, video editing, and artificial intelligence.

The processor is the core of a system-on-a-chip (SoC). Unlike desktop machine CPUs, it features a wide variety of processing options. Some of these include general purpose and digital signal processor, micro-controllers, and application specific processor. Prior to 2010, most SoCs were built with a single processor, which was responsible for controlling the whole system. In 2008, most of them were built around a processor based on one of the following processor architectures: Advanced RISC Machines (ARM), MIPS (Microprocessor without Interlocked Pipelined Stages), PowerPC, or x86. The evolution of multi-processor SoCs has raised the concerns of system designers due to their dependence on super-computing.

The bus is a major component of a SoC. Many SoCs have multiple busses, which can be used to connect various peripheral components. Some of these include the processor, memory, and hardware accelerator. The use of commercial bus protocols has been a major obstacle to the standardization of SoCs. Due to this, the use of networks on chip (NoC) has been gradually adopted.

A system-on-a-chip (SoC) is typically comprised of various control circuits, such as UART, USB, and GPS. It can also include specialized peripherals, such as FFT and turbo decoder, which are typically targeted to image processing. A hardware IP will typically provide better execution and lower power consumption than a software implementation. However, it can also increase system complexity and cost. A radio connection is provided by the addition of analog and mixed signal components. Some application domains also require specialized components such as biochips, optical computing, and millimeter wave. A generic diagram of a SoC device is included below in Figure 4.4.

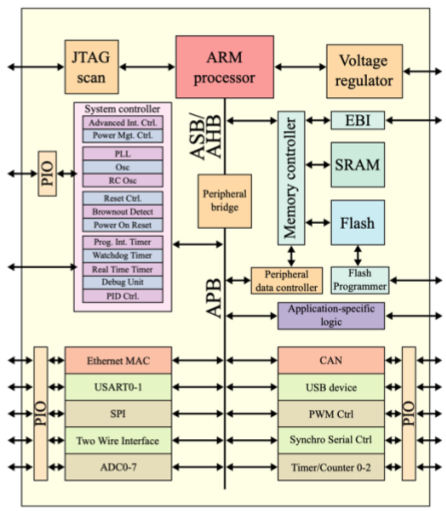

Figure 4.4: SoC Technology Diagram

The only objective metric that can be used to evaluate the quality of a system is its economic success. Among the various factors that go into this evaluation is its power consumption. The increasing number of tasks and clock rate can also affect the system's power consumption. It is difficult to predict the exact consumption of a system due to the complexity of its hardware. Techniques such as optimizing memory and clock traffic, gating clocks, and dynamically adjusting clock rate can help reduce the power consumption of system on chips. Due to the complexity of a system's design, it is critical that the system's development is performed in parallel. This is done using virtual prototyping, where the software is simulated on a virtual hardware. Depending on the complexity of the system and the implementation technology chosen, a complex trade-off can be made. Some technological choices, such as FPGAs, can provide shorter time to market. NRE cost includes the hardware and software costs, as well as the computational resources needed to complete the system's design.

4.1.5 Temperature Sensing

One of the main characteristics for this project is to accurately monitor the temperature of any given solar panel set up by the user to monitor its temperature over time and catalog the raw data in real time for further analysis.

What is a temperature sensor? A Temperature sensor is a device to measure temperature readings through electrical signals which is usually composed between two distinct types of metals or composites which generate voltage or resistance once there is a difference in temperature. In today's market a sensor designer has a wide variety of options available for temperature sensors in which there is two basic physical types to choose from Contact Temperature Sensors in which the sensor must be in physical contact with the measurable object to detect the change in temperature. The second type is Non-contact Temperature Sensor in which the object does not have to be in physical contact to measure its temperature [4.1].

On this Project will be focusing on a Contact Temperature sensor to have the ability to monitor the temperature behind any given solar cell panel in any types of configurations array. This is especially important since the main goal of this project is to be available to monitor the temperature of every single solar cell to detect any abnormalities and catalog the efficiency of different types of solar cells according to its temperature. Therefore, we will be considering only contact temperature sensors which encompass thermistors, thermocouples, RTD and diodes.

Diode as a Temperature Sensor: Diodes as a temperature transducer is a common type of application for diodes in which a moderate temperature sensing can be used for the Give an application. One of the benefits of using a diode as a temperature sensor is that linearity of the temperature coefficient Such as that it can provide negative -2mV/ºC for the overall operating range [4.2]. The most common temperature sensor using a diode is the LM335 in which has a breakdown voltage directly proportional to the absolute temperature at 10mV/Kº, low dynamic impedance of less than 1Ω, with a current operation of 400µA to 5mA [4.3]. In addition to a 25ºC calibration which gives the sensor a 1ºC error from it temperature sensing range of -50ºC to 150ºC which is highly linearized voltage over temperature output [4.3].

Thermistor: A thermistor also known as thermal resistor is a resistive load who's resistivity variates due to a change in temperature. A typical thermistor is composed of two terminals sensitive transducers composed of semiconductor-based metal oxides such as cobalt, manganese or nickel with a metallized or center connecting beat formed from a ceramic disc or bead. [4.4]. On a typical thermistor as temperature raises resistance goes down and as temperature decreases resistance increases. Thermistors offer a highly accurate resolution within a ranging from ± 0.05ºC to ±1.5ºC and depending on the bead coting it can have a temperature range as low as -50ºC to as high as 572ºC [4.5]. For most applications there are two types of resistors that can be implemented Class A thermistors that offer higher measurement accuracy and Class B thermistors that offer a lower resolution but a higher temperature range.

Thermocouple: A thermocouple is a simple and basic component the consists of two junctions of two different types of metal join at one end. By having two dissimilar metals both metals heat up at different rate which causes a temperature difference between the cold junction at the base of the wire couple and the hot junction that is connection of the wire couple at the tip of the connected metals creating a thermo-electric effect inducing a voltage measured in millivolts that can be low as 10mV [4.6]. Thermocouples temperature range is one of broadest ranges of all the current temperature sensors in the market today. Thermocouples can encompass temperature as low as -200ºC all the way to over 2000ºC, which makes it one of the most popular temperature sensors implemented on the market [4.6]. Furthermore, there are various types of thermocouples in the market with different types of sensitivity and conductor composition which affects its temperature range as we can see in Table 4.1.

Table 4.1. Types of Thermocouples

Type	Sensitivity	Conductor Material
J	0 ºC to 750 ºC	Iron/Constantan
N	0 ºC to 1250 ºC	Nicrosil/Nisil
U	0 ºC to 1450 ºC	Copper/Copper Nickel
T	-200 ºC to 350 ºC	Copper/Constantan
E	-200 ºC to 900 ºC	Nickel Chromium/Constantan
K	-200 ºC to 1250 ºC	Nickel Chromium/Nickel Aluminum

RTD: Resistance Temperature Detector (RTD) is a high-resolution temperature sensor that is made from pure conducive metals mainly platinum, copper or nickel and the wound in form of a coil similarly to an inductor. The other form of RTD is a thin film composed of platinum paste encased in a white ceramic substrate [4.6]. RTD's are like thermistors both change their resistance with a change in temperature. But unlike thermistors the output voltage of an RTD is highly linearized which means it has a higher resolution. In the other hand while an RTD has a higher resolution then a thermistor it has a much lower Sensitivity compared to a thermistor since as temperature changes it produces a small change such as 1Ω/ºC [4.6]. A standard RTD has a typical resistance of 100Ω at 0ºC in which the most implement type is Platinum Resistance Thermometer (PRT) and a range of -200ºC to over 600ºC [4.7].

Apart from the different types of contact temperature sensors there is also different wire configurations and shielding configurations that today's marketplace offers for a wide range application that offer different benefits. For instance, in some applications you want to monitor the temperature inside a corrosive environment such as in a chemistry laboratory where the lead can be exposed to corrosive chemicals, so you need a protective welded bead as seen in Figure 4.5 or shielding in your wire to prevent the distinct metals from corroding making the temperature sensor less reliable due to a change in composition.

Figure 24.5. Weld Beaded with different styles of shielding Thermocouple.

Beaded Wired Thermocouple: A Beaded Wired Thermocouple is composed of a welded bead composed of a metal alloyed. For these types of thermocouples is best to utilized when measuring the temperature of gases or non-oxidizing liquids that could corrode the metal alloyed. The main benefits of this type of thermocouple are the smaller profile then the average thermocouple and it can provide a high response time.

Non-Insolated Thermocouple: A non-insolated thermocouple just as the name implies is simply a thermocouple without a layered of insulation, this could have been done for various reason one of them is costs. If a thermocouple does not need a special shielding for the wire in higher temperature implementations or if the thermocouple is not going to be exposed to the elements.

Braid/twisted Insulated Thermocouple: A Braid/twisted thermocouple is usually an insulated thermocouple that is twisted at the tip of the junction to reduce noise picked up by the wires from nearby power wires. This is commonly use in places where a thermocouple is close by to power line or if a long wire is used to connect the thermocouple. This is due to the induced electromagnetic fields pickup by a long wire that can act as an antenna picking up unwanted environmental noise. In order to reduce this noise, we can twist the wire in such a way that the opposing magnetic fields of the wires can cancel each other reducing the receive noised leaking into the system.

As presented in the design specifications one of our requirements for this project is to be available to implement a contact temperature sensor for the "All-in-One PV Sensing node" or "All-in-One Sensor Mote" with the motive of data logging the temperature behind a solar panel. One of the flexibilities that our sponsor/client from OUC gave us is the discretion of changing the temperature sensor as the design requires but prefers the use of a thermocouple. In which case for our design, we decided to follow our sponsor/client request for the use of a thermocouple in our design.

4.1.5.1 Signal Conditioning

Signal Conditioning: Signal conditioning refers to any necessary manipulation of the voltage signal that is necessary to be available to successfully process it in the next stage of processing. In the case for a thermocouple there a necessity for signal conditioning this is due to various factors such as environmental factors and hardware limitations. Most Signal Conditioning cases that main condition signal components include but are not limited to capacitors for low and high pass filtering, operational amplifiers to amplified small voltage of sensors if the voltage too small to detect, and differential amplifiers where the voltage ratio is an issue where you run the risk of amplifying unwanted noise. The basis of signal condition can be found in the block diagram in Figure 4.6.

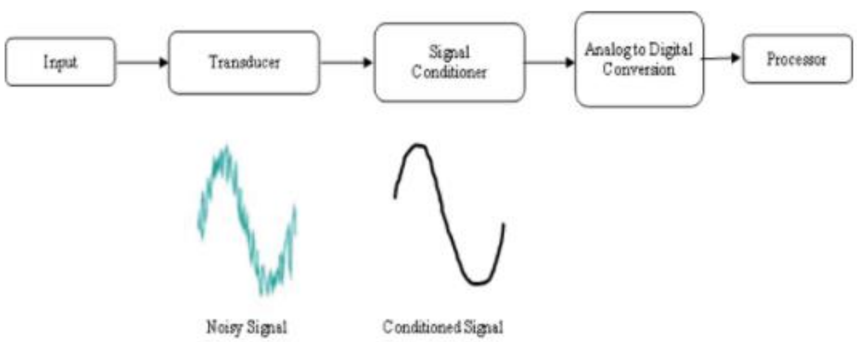

Figure 34.6. Basic Conditioning Signal Block Diagram

4.1.5.2 Signal Conditioning Wire Noise

The main reason we look at noise to voltage ratio is due to the low voltage output in mV produced by the thermocouple and its due to this that any major noise to voltage ratio would cause a significant signal misinterpretation by the hardware that is to read the signal coming from the thermocouple. Therefore, the main resolution is limited by the noise to voltage ratio of the design.

Thermocouple Wire Noise: wire noise is considered as any signal inference cause by induce crossing magnetic fields cause by EMF from nearby sources of noise such as Alternating Current devices and power lines such as the US standard of 60 HZ AC power lines in parallel with the thermocouple wire leads, AC motors and proximity to radio transmission antennas. This noise is cause by the air capacitance created by the crossing of magnetic fields if a thermocouple wire is in parallel to such power lines or rails. Creating a capacitive coupling introducing perceptible noise in our system proportional to the neighboring power current magnitude and inversely proportional to the distance of the thermocouple wires [4.8].

Thermocouple Wire Antenna Effect: Another source of noise in the wire for a thermocouple is cause by the charging effect that cause long thermocouple wires to act as an antenna receiving environmental noise from nearby radio stations, Wi-Fi, or any type of radio wave been broadcasted.

Noise to Voltage Ratio: Noise to Voltage Ratio is the ratio between the voltage output of the thermocouple according to the spectral density W/Hz of the RMS noise voltage per square root hertz or $\frac{nV}{\sqrt{Hz}}$ [4.9].

Thermocouple Resolution/Accuracy: Resolution/accuracy regarding a thermocouple refers to the smallest temperature reading produced from the smallest voltage difference created by the thermocouple. Example of such is a Type K thermocouple HI93530N has a 0.1° resolution.

The main purpose on wanting to reduce the noise to voltage ratio is due to the low voltage output in mV produced by the thermocouple in which any major noise to voltage ratio would cause a significant signal misinterpretation by the hardware that is to read the signal coming from the thermocouple. Therefore, the main resolution is limited by the noise to voltage ratio of the design. To avoid this hurdle, we can implement a couple of tested solutions offered and recommended by the thermocouple manufactures such as implementing a twisted wire thermocouple as the name implies a twisted wire thermocouple as discussed previously is a thermocouple with twisted wire in such a way where the opposing magnetic fields of the wires can cancel each other reducing the receive noised this can be viewed in Figure 4.7.

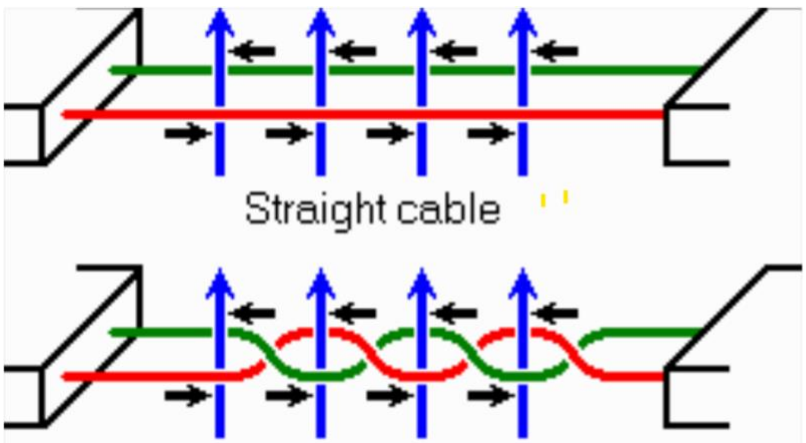

Figure 44.7. Parallel Vs Braided wire configuration

As seen in Figure 4.7 twisting the wire around we can create a short of loop along the wire also known as nodes. On this nodes Electromagnetic Fields generated from the source load will rotate when passing along from node to node creating opposite magnetic fields to those generated externally in which case, they will eventually cancel each other out.

4.1.5.3 Signal Conditioning Amplification

Another factor that noise can affect in the conditioning of the signal is that in most cases the thermocouple voltage output has to be amplified to analyze the voltage difference an increase the resolution of our design or if the hardware requires a higher voltage, then that thermocouple can be provided to detect the voltage properly. Therefore, if a noise is introduced before the amplification circuitry the noise can be amplified leading to a high noise to voltage ratio reducing our resolution.

Operational amplifier: An operational amplifier (op-amp) is at its core voltage amplification integrated circuit or IC that can amplified a weak electrical signal usually in range of millivolts. The typical operational amplifier has a differential input where there are two input pins and one output pin [4.10]. The purpose of having two input pins is to output the voltage difference between the two input pins giving you an amplified voltage by the ratio factor of the two input pins called GAIN.

Differential amplifier: A differential amplifier behaves similarly to an operational amplifier in which the difference between the two inputting voltage pins gets amplified producing the amplified voltage in the output pin [4.11]. The main difference is that the differential amplifier also suppresses the common voltage between the two pins reducing noise in the amplified signal. This is the main implementation of a differential amplifier is mainly used to suppress noise generated by the wires of the given component that needs amplification which induces an electromatic induction called noise due to the potential difference of the signal source ground and circuit ground [4.12].

4.1.6 DATALOGGERS

One of the main market offerings for Photo Voltaic data logging is the use of data logger in which you can connect a great variety of analog outputting sensors. In this case once all the sensors are connected to the data logger one can access the results through a live server usually provided by the manufacturer.

Furthermore, this type of data loggers has multiple ADCs making a great choice for analog sensors. In addition to this every single input of the datalogger offers low noise amplification providing need it filtering for sensors that tend to have noise mix in their output.

While the data logger is a great choice for monitoring a PV system and data log raw data is not a great economic way to data log data. Furthermore, it requires the usage of additional equipment or sensors to monitor parts of the PV system in which case very single added sensor needs to be routed to the main data logger adding to the cost of installation further increasing costs.

One such example of how a data logger can be used as a PV monitoring system can be found in our sponsor's OUC testing facility. On their testing array they have installed a data logger with cables going underground coming from all the sensors connected to the solar panel array installation area. As we can see in Figure 4.8 OUC Datalogger PV monitoring system not only requires all sensors to be externally connected to the datalogger it also requires the use of a bulky power supply.

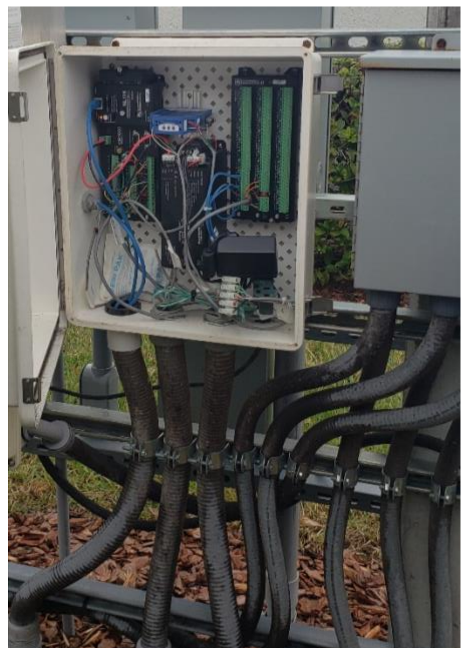

Figure 4.8. Facility OUC Datalogger PV monitoring Systems for Solar Testing Array

4.2 MARKET ANALYSIS & EXISTING EFFORTS

In this subsection, existing applications of current and voltage focused inclusive sensors will be investigated and discussed for our engineering prototype. These will provide a strong groundwork for the ideologies that will be included in our design and allow us to reflect on the work of those before us for inspiration.

4.2.1 TIDA-00640

Our team was unable to find any commercially available products that were able to 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 whose block diagram is seen in Figure 4.9. 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 [4.13].

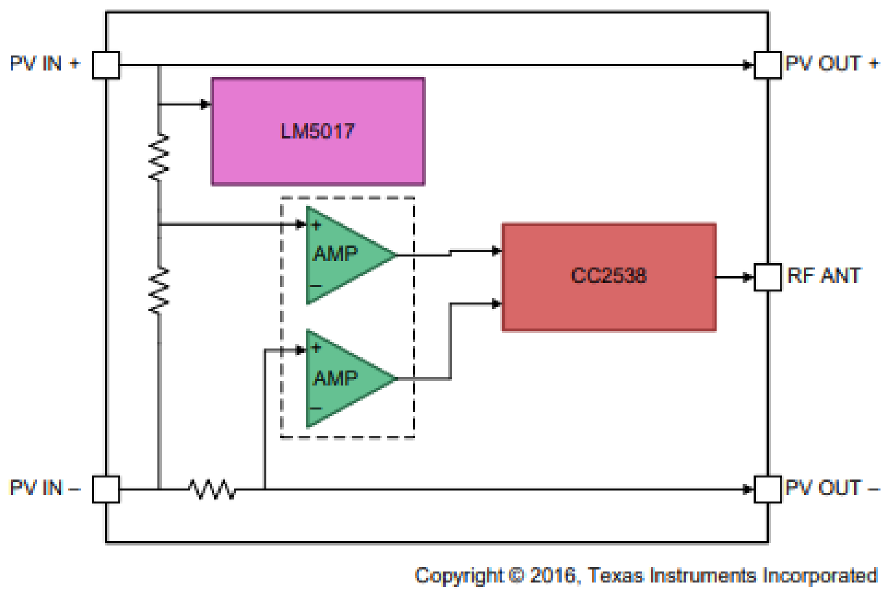

Figure 4.9. TIDA-00640 Block Diagram

The scope of the TIDA-00640's design is similar to our project's 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.

It's important to understand how the TIDA-00640 is interconnected so that we may further understand the inner operations of it. For example, it would be best to understand how it senses voltage, current, & temperature, how the board is powered, and how the data leaves the board to a local database.

Similar to our design choice, the TIDA-00640 uses a simple voltage divider alongside a amplifying configuration to measure the panel voltage. Because their full-range output from the panel is around 90 V, they needed to step down the voltage to a more acceptable level to give their circuitry some room to breathe. Their voltage divider decreased the input voltage by a factor of 50.8 giving them a final voltage of around 1.77V. High value resistors were used to limit power loss in the divider and to minimize current draw from the panels. With a total drop of 510 kiloohms, the voltage divider draws only 177 uA from the panel.

Concerning their current measurement, the TIDA-00640 makes use of a low-value current shunt resistor. They elected to do this to keep system complexity at a minimum and due to their sensor's location. Had they elected to be placed at the input of their MLPE module and not the output, then they would have had to account for a single module's current rather than an entire string. Their shunt resistor should be able to handle a maximum of 10 A, similar to the design requested by OUC. In a typical 300-W solar module, the power loss caused by the existence of a shunt resistor with a resistance value of 1 milliohm to measure current is a negligible 0.03%. The value passed to the ADC is the voltage measured across this small resistor. Due to this voltage being 0.01V even when a maximum of 10A is passing through the shunt resistor, this value is increased by a factor of 260 using an amplifying configuration to give an overhead of about 2.6V to be sent to the ADC.

The TIDA-00640's temperature sensor is a derivative of the TIDA-00649's temperature sensing functionality which is also a derivative of the internal analog temperature sensor present in the CC2538. This temperature sensor measures the system level temperature at the module level rather than at the power electronics, serving to be a part of a larger system level. This is unlike what we aim to do with our All-In-One PV Sensor. The thermocouple that we are implementing to measure temperature will be measuring the direct temperature of the panel and not any internal temperatures of our hardware.

On the other hand, the TIDA-00640's power supply is almost identical to the intended power supply for the All-In-One PV Sensor; the TIDA-00640 is fully powered by the solar module that it is measuring. This is possible due to the selected LM5017 step-down regulator. The original output voltage that the team at TI faced was upwards to 90 V which could not power a PCB without frying their intended components. With the introduction of the LM5017, they were able to decrease any voltage in the range of 7.5 to 100 V to a more acceptable 3.3V required for their design.

Finally, it's important to understand how the TIDA-00640 transmits its data from the on-board ADC to a wireless database for data analysis. The CC2538 was mentioned in the temperature sensor section, and it continues to have its uses in wireless transmission. The CC2538 is made with an integrated IEE 802.15.4 wireless radio supporting ZigBee PRO/2.0, ZigBee 3.0, and Contiki to transmit data for their personal reasons, TI chose to use ZigBee to send their data. While both these sensors and the All-In-One PV sensor will transmit data wirelessly, they will not be using similar transmission technologies.

4.2.2 OpenGreenEnergy

The TIDA-00640 was the closest the team could find to a mainstream product that reflected our goals and needs. However, there do exist personal research projects and hobbyist materials that also aim to monitor and evaluate connected PV systems. While these projects may not be able to accommodate the same voltage or current ranges that our All-In-One Sensor aims to, they should still be researched to review their thought processes and any observations they have made along the way.

One such project was created by a hobbyist identified as OpenGreenEnergy who created detailed instructions to create a DIY Solar Panel Monitoring system for small-scale PV systems [4.14]. While this system's specifications are lower than what OUC requires and therefore cannot be replicated to fit our requirements, understanding what OpenGreenEnergy set out to achieve and how they achieved it is ultimately more important to understand.

OpenGreenEnergy's design can measure the voltage, current, and ambient temperature of the panel, and is able to send that data wirelessly to Blynk, an app platform popular with Internet of Things users. This design measures voltages by using a voltage divider, current by using the AC723 hall effect current sensor, and ambient temperature with the DS18B20 temperature sensor. Similarly, to our tentative design, OpenGreenEnergy's concept uses the ESP32 for all calculations and wireless communications. Figure 4.10 lists all relevant components of OpenGreenEnergy's design.

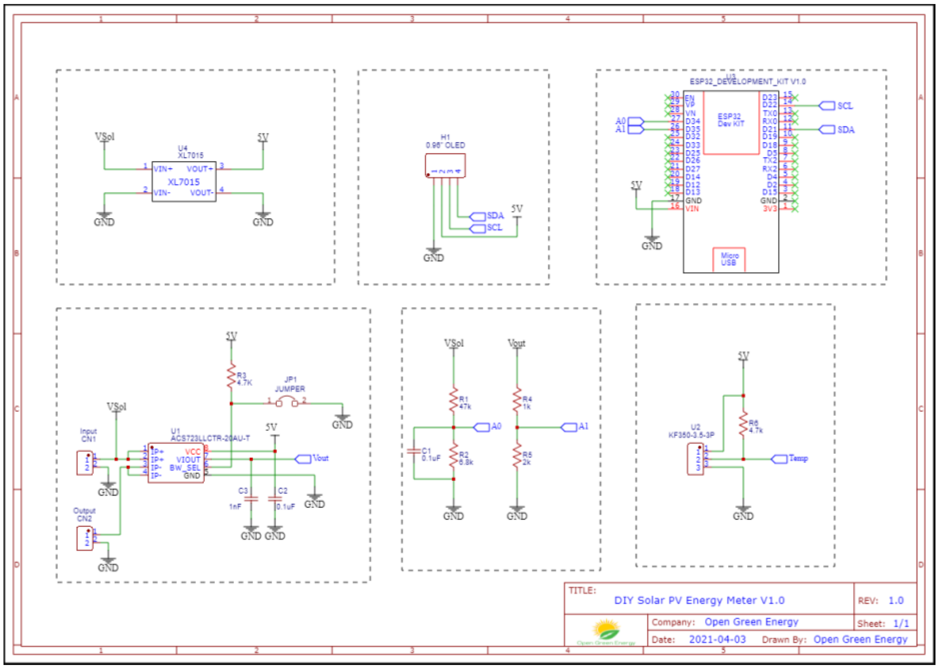

Figure 4.10. In order, from top left to bottom right: XL7015, ESP32, Current Sensor, Voltage Sensor, and Temperature Sensor schematic

A key component of this design is the XL7015 buck converter. This is a DC-to-DC step-down module that converts a maximum voltage of 80 V down to 5V. In this design, this converted voltage will act as the supply voltage for the ESP32 and the AC723 Current Sensor. The main takeaway from this design is this component – the existence of a converter is crucial to our project to ensure that the high voltages received from the solar panel will be small enough to power our components without burning them.

4.3 Component Selection and Implementation

In this section, the specifications of what is required for the functionality of the All-In-One PV Sensor is greatly scrutinized. We will take a deep look at the numerous sections of hardware and software involved in the creation of the All-In-One PV Sensor and understand what components will fit best in our design. Major components are selected definitively such that prototyping can begin, but many of the smaller and more volatile components may see changes based on chip availability. Decisions will be made as necessary for the health of the All-In-One PV Sensor.

4.3.1 ADC Considerations

Analog to Digital Converters (ADC)

The primary source of data in this project will be the voltages and currents generated by and received from the Solar Panel. The solar panel will output purely analog, nearly DC signals for our circuitry to sense and deliver wirelessly to a collector node. An Analog to Digital Converter, or ADC, is able to take an analog signal as an input and transform it to an easier to understand and represent signal in a digital format. In this application, an ADC is able to accept an analog input voltage or current and represent it as a digital number reflecting that measured value’s magnitude. This will allow our selected microcontroller to read, interpret, and transmit the necessary data.

The data that this All-In-One PV Sensor will process will not be too large or demanding, so the ADC can be cheaper or feature lower resolutions compared to more industrial applications. A comparable All-In-One PV sensor created for in-house use by TI, the TIDA-00640, makes use of a 12-bit ADC with eight channels, so we could expect to use similar or lower resolution equivalent ADCs.

ADC Constraints

The existence of an external ADC in this project is entirely dependent on the MCU that is selected to transmit data – for example, if a Raspberry Pi model were to be selected, certain Raspberry Pi compatible ADCs would need to be considered. If a model that includes an ADC were to be selected, such as an ESP32, then an ADC would be unnecessary as it would already be present in the chip. Therefore, a large selection is required to future-proof this design.

All sensors will require an ADC, regardless of their configurations and selections of pyranometers or thermocouples as the solar panel will always send an analog voltage and current signal. Therefore, the ADC must be considerably cheap to minimize the overall cost of the All-In-One PV Sensor.

ADC Considerations – External, Surface-mounted ADC

In this section, the possibility that an MCU is selected that is not the Raspberry Pi OR a chip that includes a built-in ADC. Therefore, the considered ADCs will be surface mounted to the PCB for all other sensor elements to connect to.

MCP3428: This 16-bit, dual channel ADC has 4 differential inputs with an analog supply voltage of 2.7 to 5.5V and a singular unit price-point of $3.11. This sensor is low noise and high accuracy and can output up to 240 samples per second when employed under its 12-bit mode. It features both one-shot conversion and continuous conversions which is suitable for both rapid data streams and considerably slower data processing speeds. [4.15]

ADC084S051CIMM/NOPB: This ADC is 8-bits with 4 inputs to accommodate for all of the possible inputs in one All-In-One PV Sensor. It has a single unit price of $2.94 and operates with a single power supply that can range from 2.7 V to 5.25V. However, it is limited by this – this ADC’s analog input voltage must fall between 0V and its supply voltage, severely limiting this ADC’s ability to function in higher voltage environments.

ADC Considerations – Raspberry Pi Extensions

In this section, the possibility that a Raspberry Pi is selected is considered. Certain models of Raspberry Pi can transmit data wirelessly and connecting an ADC to that Pi would allow the ADC to communicate directly with the wireless transmitter.

MCP3008: This ADC is low-cost, 8-channel, and 10-bit. It has a single unit price of around $4.50 and pairs extremely well with the Raspberry Pi and its respective models. It connects directly to the Pi using an SPI serial connection and the additional channels have designated connections to all Raspberry Pi models. For example, the VDD and VREF of the MCP3008 will always connect to the Pi’s 3.3V pin. [4.16]

ADS1015/ADS1115: These two ADCs are of the same branch. The ADS1015 is a 12-bit, 4-channel ADC that utilizes I2C communication to interact with the Raspberry Pi. The ADS1115, on the other hand, is an improved 1015 with a higher precision featuring 16-bits rather than 12. Because of the nature of our project, these higher bit counts are only necessary if a higher-than-expected accuracy is required from the ADC. For this reason, these parts will only be considered if that condition comes about, as they are priced much higher than the MCP3008 at $9.95 and $14.95, respectively. [4.16]

ADC Considerations – A review of possible chips with built-in ADCs

In this section, rather than focusing on adding an ADC to our board, we'll review the features of the ADC on any possible MCU or Wireless Transmitter that is considered for our final design.

ESP32: The ESP32 is a low-cost and low-power microcontroller that has Wi-Fi and Bluetooth capabilities. For this reason, the ESP32 is being considered to replace the Raspberry Pi for wireless transmission in addition to its market availability. Models of the ESP32 can integrate two 12-bit SAR ADCs, supporting up to 18 measurement channels which is far more than the project requires. An average ESP32 microcontroller is valued at ~$10 and is considerably cheap when considering its additional features. [4.17]

MSP430BT5190: This MSP controller has a 12-bit ADC with Bluetooth functionality which is enough to transmit data over a range of about 20 meters. For this project, that range is acceptable, but future endeavors may seek other wireless transmission. However, this chip is expensive compared to even an external ADC, so the only thing that can be taken from this controller are its ideals. The high-performing clock would allow us to retrieve data from the Solar Panel and translate it at much higher rates which would be ideal for rapid data collection and analysis.

Table 4.2 provides a summary of these findings.

Table 4.2 Summary of ADCs and their Categories

ADC	External/Surface Mount	Raspberry Pi Ext.	ADC in MCU
Top Choice	ADC084S051CIMM	MCP3008	ESP32
Samples per Second	200 to 500 ksps	200 ksps	200 ksps
Communication Interface	SPI	SPI	Directly to MCU
Input Channels	4 inputs	8 inputs	Up to 18 inputs
Price	$2.94	$4.50	$10 for chip

4.3.2 Microcontroller and Microprocessor

We will be implementing two logic devices in our design: a microcontroller, ESP32-WROOM-32, and a microprocessor, Raspberry Pi 4 Model B+. This section will explain the details of these devices.

4.3.2.1 ESP32

The ESP32 is a low-power SoC developed by Espressif Systems which possesses both Wi-Fi and Bluetooth wireless communication capabilities. There are many variants of the ESP32 microprocessor, like the ESP32-D0WD-V3, ESP32-U4WDH, ESP32-S0WD, any many more. The variant we will be implementing in our design is the ESP32-WROOM-32, which features many functions that will help satisfy our design requirements like multi-channel analog to digital converters (ADC), digital to analog converters (DAC), multiple general-purpose input/output (GPIO) pins, serial peripheral interface (SPI), Inter-Integrated Circuit (I2C), universal asynchronous receiver-transmitter (UART), variable input power voltage, among many others. The comprehensive ESP32 block diagram is pictured in Figure 4.11.

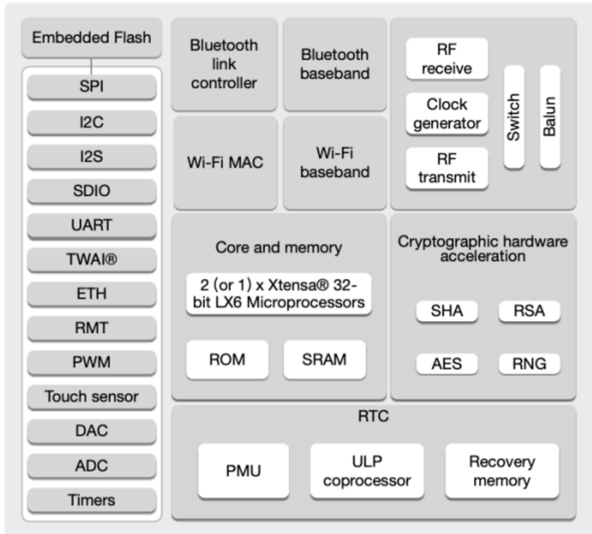

Figure 4.11. ESP32 Functional Block Diagram

Figure 4.12 features the pin layout of the ESP32, which we will heavily depend on when inserting the ESP32 chip into our PCB and connecting busses from our four (4) sensor devices.

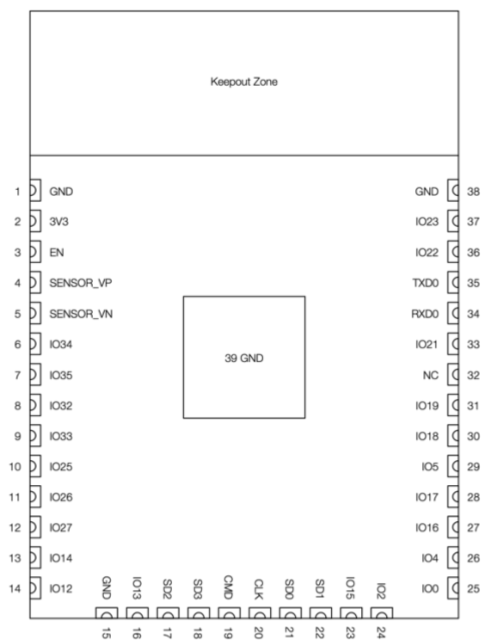

Figure 4.12. ESP32-WROOM-32 Pin Layout

4.3.2.2 RASPBERRY PI

The Raspberry Pi is a series of single-board computers made by the Raspberry Pi Foundation. It was originally developed to promote basic computer science education in developing nations. The original model was initially targeted to hobbyists and roboticists, but it has since been used in various other applications. After the release of the second model, the Raspberry Pi Foundation was renamed to Raspberry Pi Trading, and it was headed by Eben Upton.

The Raspberry Pi 4 Model B was released in June 2019. It featured a 1.5 GHz 64-bit quad core processor, 8 GB of RAM, and support for dual-monitor setups. The Pi 4 has a slightly lower price tag with 8 GB of RAM. It's also powered by a USB-C port, and it can be operated with 5 volts. The initial Raspberry Pi 4 had a design flaw that prevented third-party cables from identifying it and refusing to provide power. This issue was corrected in the 1.2 revision of the board. In 2021, the Pi 4 B variants started receiving an improved version of the Broadcom BCM2711C0, which is used for the Pi 400 and the Pi 4 B. The model we will be implementing in our design is the Raspberry Pi 4 B+ as in Figure 4.13.

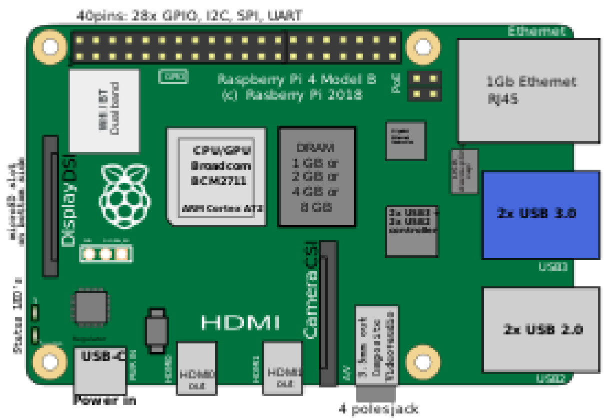

Figure 4.13: Raspberry Pi 4 B+ Diagram

Since its inception the Pi has been a cutting-edge piece of modern technology as it contains all that a consumer computer would need to operate on a single board the size of a credit card. This means you can plug a monitor, peripherals like mouse, keyboard, and speakers, all into a single Pi. As described earlier, the Pi contains all the technology that any other SoC offers and more. We will be using a Pi in our design as the hub where all the data from our multiple ESP32 devices will be sending data to. The Pi will compile all our data into a database so that OUC can easily access and analyze data collected by our AIO sensor.

4.3.3 Current Sensor

One of the requirements of the OUC was to incorporate a current sensor into our circuit design. This would be used to accurately measure and monitor the current flowing out of the solar panel, giving the result in 10 second intervals. This was a task that the previous group was unable to achieve with their design; I this section, we would look at different methods we can use to gain the desired result. First let us understand the tool that will be used to sense current flow in the All-In-One PV sensor
Current sense Resistor:
The current sense or shunt resistor is a resistor, typically with a low resistance value, which the load current flows into in a current sensing circuit. According to TI "The value of the resistor is usually based on achieving a desired maximum differential voltage at the highest expected current. The resistor value may also be based on the power-loss budget." We have already been given the highest expected current and the power range of the panel, so we can determine the right shunt for the operation.

Another important consideration is the resistors tolerance since this has a direct impact on the accuracy of our measurement. A higher tolerance means it has a higher percentage of error, while a lower tolerance means the resistor has a lower percentage of error; so, we would get the lowest taking into consideration the price. There is also the resistor temperature coefficient; due to power dissipated, and environmental factors, the resistors value could be affected if the tolerance is too low. Since the sensor would be outside, and current would be flowing through the shunt, a resistor that can manage high temperature would be used. A typical shunt resistor configuration can be seen in Figure 4.14.

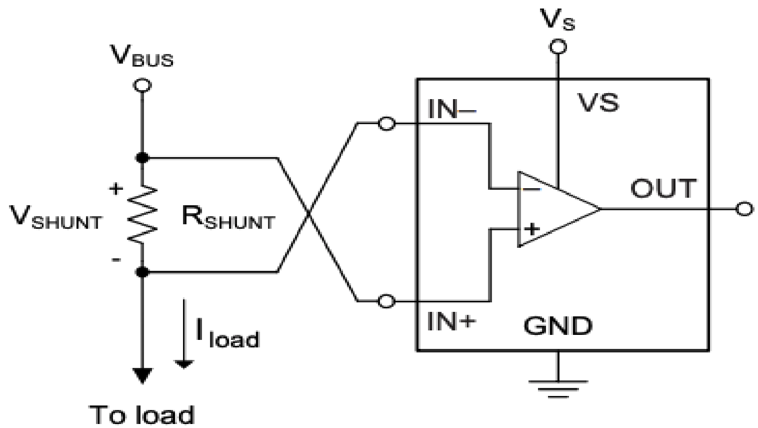

Figure 4.14. Shunt Resistor configuration.

Table 4.3 features the possible shunt resistor packages that we could use in the implementation of the current sensing circuitry in the All-In-One PV Sensor.

Table 4.3: Possible Shunt Resistor Packages for the All-In-One PV Sensor

PACKAGE	TOLERANCE (%)	RESISTANCE (mΩ)	POWER RATING (W)	UNIT PRICE ($)
805	1	10	0.5	0.53
1206	1	10	1	0.64
2512	1	10	2	0.65
1206	0.5	10	0.5	0.74
2512	0.5	10	1	1.66
2512 wide	0.5	10	2	2.16

<u>Current sense Amplifier</u>

Now we know what device allows the current to flow through, then what measures the current. This is where the current sense amplifier comes into play. The Current sense amplifiers, also called current shunt monitors, are specialized differential amplifiers which measure the voltage drop across a sense element; in this case it would be the shunt. We can understand how they do this when we consider ohms law; V=I/R, if the resistor value is low enough, the values of the voltage would be very close to the current value. The Amplifier amplifies the voltage signal, and the ADC reads a voltage value that is like the current. They are normally easy to use and tend to be precise and less prone to noise. They can support a wide range of current, and can support common-mode voltages from -16 to +80 V.

<u>Key parameters</u>

When choosing the Amplifier, there are some key parameters to consider:

Common Mode Range: the DC voltage range at the input of an amplifier with respect to ground. Current sense amplifiers are typically designed to support common-mode voltages well beyond the chip supply voltage. For example, an IC can support a common-mode voltages between -8 V to +70 V while running on a supply as low as 2.1 V.

Offset Voltage: This is a differential DC error at the input of the amplifier. ICs are able to offer current sense amplifiers with offsets as low as 10µV, enabling higher precision measurements at low currents and allowing the use of smaller value shunt resistors. Ideally this voltage would be zero, but in reality, it is always a non-zero voltage. Small offset voltages can lead to large errors, which can increase over device age and operational temperature.

Gain: Current sense amplifiers have a variety of gain options, that have different performances over temperature and shunt resistance value

Temperature Stability: According to TI, "Current sense amplifiers integrate the amplifier along with all the gain-setting resistors which enables small and unified temperature drift. This allows for robust current measurements across the whole specified temperature range. The achieved temperature stability is one of the key advantages current sense amplifiers have over discrete implementations."
Design consideration:

There are three main design considerations when choosing the amplifier:
High-Side Measurements: This is a sensing technique that involves placing the sense resistor between the supply voltage and the load. This system directly monitors the current delivered by the supply, which allows for the detection of load shorts. High-side current sensing does not create ground disturbances. Ground disturbances are problematic when other circuits in a system are required to interface with the load. Placing the shunt resistor above the load, as in high-side current sensing, eliminates ground disturbances because the shunt resistor is no longer connected directly to ground. In high-side current sensing, the shunt resistor remains in the circuit and can detect a surge in current from a short to ground condition.
The main disadvantage is that because the shunt resistor is not at system ground, a differential voltage must be measured which requires the precise matching of the proper differential amplifier. A sample High-Side configuration can be seen in Figure 4.15.

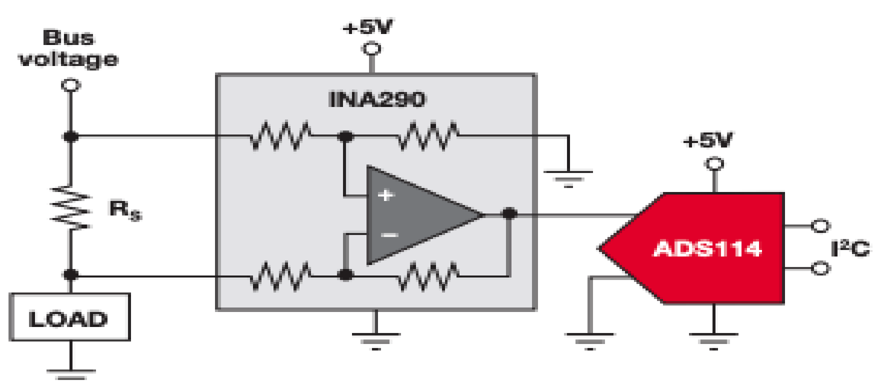

Figure 4.15. High-Side Shunt Resistance Measurement

Low-Side Measurements: This is a sensing technique that involves placing the sense resistor between the Load and the ground. In this design, the common-mode voltage is near ground, which allows for the use of single-supply, rail-to-rail input/output op amps. Low-side sensing is often the least expensive and simplest method to implement because if one end of the sense resistor is at system ground, and the other end of the resistor is at the ground side of the load whose current is to be measured, then the voltage across the resistor with respect to system ground can be amplified by a simple op-amp referencing the same system ground.
The disadvantage of low-side sensing is related to its advantage, placing a resistor in the load's path to ground. This resistor placement results in the load's ground floating at a slightly higher voltage than the

system ground. The most common issue with this arrangement is potential ground loop problems. Since the load is not at the same ground potential as the other loads in the system, the system can develop an audible noise, such as a hum, or even produce interference with nearby equipment, including audio and video interference. In addition, low side sensing cannot detect fault conditions such as a short or open circuit in the ground path due to connection problems or outside interference. A sample low-side configuration can be seen in Figure 4.16.

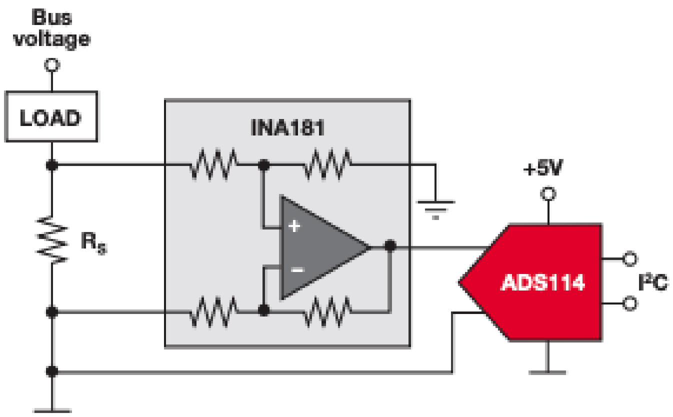

Figure 4.16. Low-Side Configuration

In-line Measurements: This current sensing technique connects the current sense element in-line to the load. Here, the current being passed across the motor is measured and used in feedback and control calculations. During the slew of the PWM signal, the inputs of the amplifier are exposed to a signal that is quickly moving approximately between ground and a large input voltage. This exposure leads to large common-mode transients being injected into the amplifier; nonideal for a device attempting to pass a precise measurement for the purposes of feedback control. This can be seen in Figure 4.17.

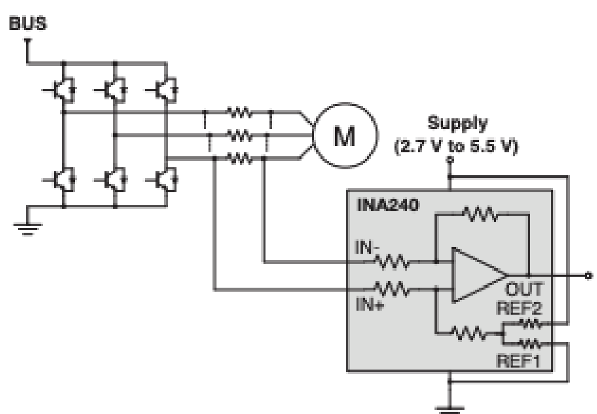

Figure 4.17. In-line Configuration

The configuration for this design would be the low-side sensing technique. It is more applicable for the sensor we are designing.

<u>Current Sense ICs</u>

Looking into the amplifiers that we could use, there were four integrated circuit (IC) that stood out, 3 current sense amplifiers, and one Operational amplifier. The main factor of choosing the IC is the current and voltage sensing capability.

INA219: It is a bidirectional current shunt and power monitor with an I 2C- or SMBUS-compatible interface. The device monitors both shunt voltage drop and bus supply voltage, with programmable conversion times and filtering. A programmable calibration value, combined with an internal multiplier, enables direct readouts of current in amperes. The two analog inputs to the INA219, IN+ and IN–, connect to a shunt resistor in the bus of interest. The INA219 is typically powered by a separate supply from 3 to 5.5 V. The bus being sensed can vary from 0 to 26 V. There are no special considerations for power-supply sequencing (for example, a bus voltage can be present with the supply voltage off, and vice-versa). The INA219 senses the small drop across the shunt for shunt voltage and senses the voltage with respect to ground from IN– for the bus voltage.

INA3221: It is a three-channel, high-side current and bus voltage monitor with an I 2C- and SMBUS compatible interface. The INA3221 monitors both shunt voltage drops and bus supply voltages, in addition to having programmable conversion times and averaging modes for these signals. The INA3221 is a current-shunt and bus voltage monitor that communicates over an I 2C- and SMBus-compatible interface. The INA3221 performs two measurements on up to three power supplies of interest. The voltage developed from the load current passing through a shunt resistor creates a shunt voltage that is measured between the IN+ and IN– pins. The device also internally measures the power-supply bus voltage at the IN– pin for each channel. The differential shunt voltage is measured with respect to the IN– pin, and the bus voltage is measured with respect to ground. The INA3221 is typically powered by a separate power supply that ranges from 2.7 V to 5.5 V. The monitored supply buses range from 0 V to 26 V.

LM5056A: It combines high-performance analog and digital technology with a PMBus complaint SMBus and I2C interface to accurately measure the electrical operating conditions of systems connected to a backplane power bus. LM5056/LM5056A continuously supplies real-time power, voltage, current, temperature and fault data to the system management host via the SMBus interface. The LM5056/LM5056A provides intelligent monitoring of the input voltage, output voltage, input current, input power, temperature, and an auxiliary input. The LM5056/LM5056A is enabled by increasing the input voltage on VIN above the POREN threshold voltage, typically 8.7 V. There exists a VDD power on reset (VDDPOR) threshold on VDD of 3.8 V. The VDDPOR threshold must be surpassed to ensure proper telemetry readings. VDD must be powered externally by a 5 V power supply with an allowable tolerance of ±10%.The SMBus address of the LM5056/LM5056A is captured based on the states of the ADR0, ADR1, and ADR2 pins (GND, NC, VDD) during turn on and is latched into a volatile register once VDD has exceeded its POR threshold of 3.8 V. Reassigning or postponing the address capture is accomplished by holding the VREF pin to AGND.

TLV342IDR: The TLV34xx devices are single and dual CMOS operational amplifiers, respectively, with low-voltage, low-power, and rail-to-rail output swing capabilities. These single-supply amplifiers are designed specifically for ultra-low-voltage (1.5 V to 5 V) operation, with a common-mode input voltage range that typically extends from –0.2 V to 0.5 V from the positive supply rail. The supply voltage must be chosen such that it is larger than the input voltage range and output voltage range. For instance, this application scales a signal of ±0.5 V to ±1.8 V. Setting the supply at ± 2 V is sufficient to accommodate this application. The supplies can power up in any order; however, neither supply can be of opposite polarity relative to ground at any time; otherwise, a large current can flow though the input ESD diodes. TI highly recommends adding a series resistor to the grounded input to limit current in such an occurrence. Vsup+ must be always more positive than Vsup–; otherwise, a large reverse supply current may flow.

Current Sense Amplifier Comparison

Given the option of IC's that could possibly be use, we would now look at the specification of each device, comparing them to see which one could potentially be used as an amplifier for the All-In-One PV sensor. Table 4.4 provides a comparison of a few ICs.

Table 4.4: A comparison of Current Sense Amplifier Integrated-Chips

Current Amplifier	INA219	INA3221	LM5056A
Common mode voltage (Min) (V)	0	0	10
Input offset (+/-) (Max) (uV)	50 100	80	300
Input offset drift (+/-) (Typ) (uV/C)	0.1	0.1	
Gain (V/V)	1 0.5 0.25 0.125	1	1 0.5
Gain error drift (+/-) (Max) (ppm/°C)	83	50	
Bandwidth (kHz)	5.5	3.5	0.5
Supply voltage (Max) (V)	5.5	5.5	80
Supply voltage (Min) (V)	3	2.7	10
Iq (Max) (mA)	1	0.35	6.8
Digital interface	I2C SMBus	I2C SMBus	I2C PMBus SMBus
Features	Bi-directional Programmable Gain	Alert Function Bi-directional Low-side Capable	Digital Temp Monitor
Approx. price (USD)	$0.840 | 1ku	$1.575 | 1ku	$2.048 | 1ku

After looking at the specifications of the IC's, the probable choice for the current sensor would be the TLV342IDR. All the components have their benefit, and they can perform the operation we need. However, the TLV342IDR has an edge in necessity and price. We would need the device to sense the current from the solar panel, we would not need the other features the other IC's present. As a result, the TLV342IDR would be more efficient, also due to the features of the IC's, they become pricier, so the amplifier presents the cost-effective option. The other component that could be likely used would be the INA219, this would be due to its precision in its reading. Figure 4.18 shows a TLV342IDR current sensing configuration.

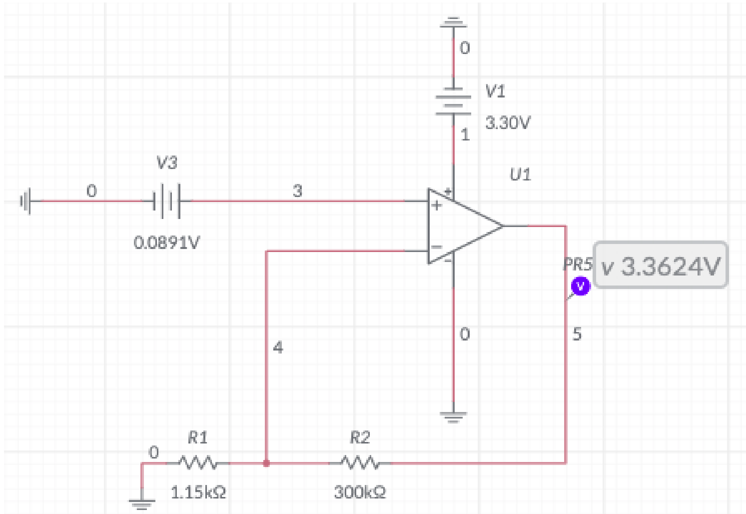

Figure 4.18. *TLV342IDR Current Sensing Application*

To measure the current from the solar panel, we must construct a differential amplifier circuit connected to the pins of the TLV3421DR. We aimed to achieve a result without saturation, so 2.3 - 2.5 V range was chosen to be sent to the ADC. The voltage coming through the shunt would be exceptionally low approximately 0.00891 V (8.91 A x 0.001 Ω), so we calculated a gain that would boost the voltage going to the ADC. We used a 1.15 kΩ and 334 kΩ precision resistor to get an overhead gain of 261; this makes the final voltage 2.6 V (V=10 A x 0.001 Ω x 261 = 2.6 V).

4.3.4 Voltage Sensor

A voltage divider is a passive circuit element that is used to provide different voltage levels from a common supply voltage. This is also known as a potential divider as it takes the amount potential difference between two points. This divider takes advantage of the effect that occurs when a voltage drops across components connected in series. In essence, the voltage divider turns large voltages into smaller ones. The main purpose of the design is to measure the voltage across a resistor R2. The value would end up being a fraction of our input voltage(V1). This can be represented mathematically through the equation:

$$V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2}$$

As seen in this equation, the output voltage is directly proportional to the input voltage and the ratio of R1 and R2. So, by using a greater value of R2, we would be able to get a more accurate voltage reading. This is a simple and effective design that we would implement into our PCB to measure the voltage from the solar panel.

Voltage Sense IC:

We would need an integrated circuit that would be able to measure and handle the panel's voltage. Adding different ICs to calculate voltage and current separately could become complex, fortunately we can use one IC to perform both measurements. As already discussed, the component that would be used is the TLV342IDR. This buffer amplifier would feed the voltage to an analogue to digital converter. The main issue would be the input voltage of the solar panel, which ranges from 32-39 volts. The IC can take only between 1.8-5 volts, so to counteract this, the voltage would be stepped down to the suitable range which the IC can operate in. Figure 4.19 shows our intended TLV342IDR Voltage Sensing application.

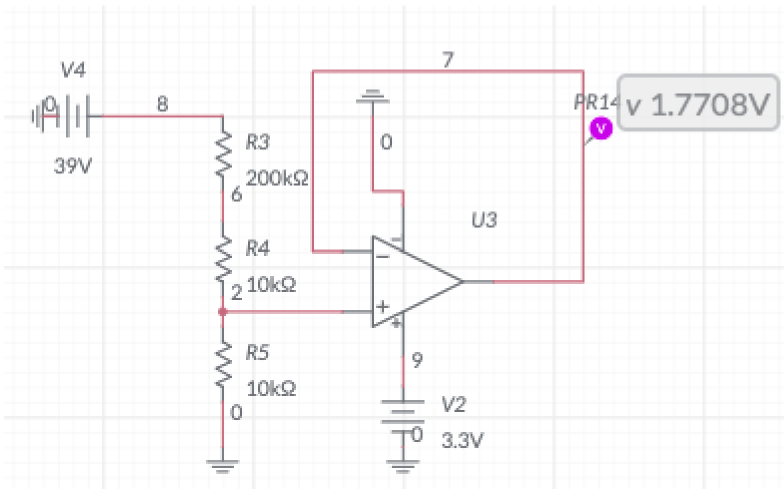

Figure 4.19. TLV342IDR Voltage Sensing Application

For our voltage sensor, we were using the direct voltage from the solar panel. The panel outputs 39 V max, but our IC can only handle between 1.5 to 5 V, and the ESP 32-WROOM-32 can handle 3.3 V max, so we had to reduce the output voltage. To solve this issue, we used a 10 kΩ and 210 kΩ resistor; this allowed a maximum voltage of 1.77 V (39 V x (10 kΩ / (10 kΩ + 210 kΩ))) to be read by the ADC. The unity gain buffer provided no gain, but it reduced the power consumption as power use increases if the current increase (P = I x V), so the unity gain buffer minimizes current supply making it efficient for power reduction.

<u>Circuit Design</u>

Now that we know the parts that would be involved in current and voltage sensor, we then must incorporate these components. To design a circuit that contains these sensors, we looked for inspiration through some previously designed circuits that performs the intended function. The circuits we researched on are essentially reference designs to be used for our final product.

<u>Reference Designs</u>

In this section, we will discuss these reference designs in which we either considered and/or will be implementing in our design.

TIDA-00795: The TIDA-00795 Automotive Precision eFuse reference design is a replacement to the traditional fuse, offering overcurrent protection with higher accuracy and features not found in traditional fuses. This TI Design can be used as a building block to implement a multichannel eFuse box.

To sense current, the design uses a INA300-Q1; this is a high common-mode, current-sensing comparator that is configured to detect overcurrent conditions through measuring the voltage developed across a current sensing or shunt resistor. The device can measure this differential voltage signal on common-mode voltages that can vary from 0 V up to 36 V, independent of the supply voltage. The device features an adjustable threshold range that is set using a single external limit-setting resistor. The device has a good voltage rating, but it falls short of the 39-32 voltage output of the solar panel.

To regulate the power supply, the design takes advantage of the LM9036Q. The LM9036Q ultra-low quiescent current regulator features low dropout voltage and low current in the standby mode. With less than 25-µA ground pin current at a 0.1-mA load, the LM9036Q is ideally suited for automotive and other battery-operated systems. The LM9036Q retains all the features that are common to low dropout regulators, including a low dropout PNP pass device, short circuit protection, reverse battery protection, and thermal shutdown. The TIDA-00796 Block Diagram is seen in Figure 4.20.

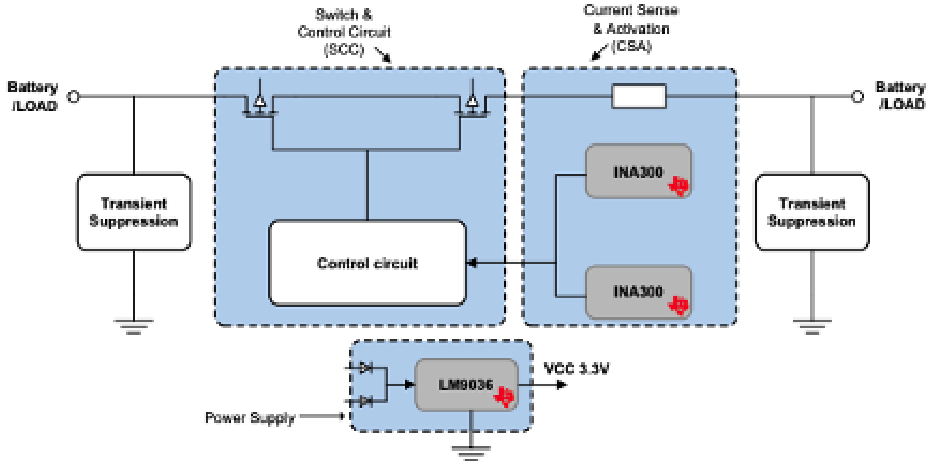

Figure 4.20.: TIDA-00795 Block Diagram

One of the main issues with this design is the input voltage requirement. According to the datasheet, the maximum operating voltage of the system is 28 volts, which is below the minimum voltage the solar panel outputs. Also, this design does not use an ADC. Table 4.5 summarizes the TIDA-00795's specifications.

Table 4.5 TIDA-00795 Voltage Sensing Specifications

PARAMETER	SPECIFICATIONS
Voltage Input	DC input operating voltage –28 to 28 V
ION_TIME Output current on time	Output load current: ≤ 30 A, 2.2 to 3.5 ms
VON_TIME Output current on time	I LOAD ≤ 30 A, Null
VOFF_TIME Output current on time	I LOAD = 30 A Input source off; output current less than 10 %
Design accuracy	97.36%
Resistance	Average measured turn on resistance of eFuse design

TIDA-00528: This verified design can accurately measure current, voltage and power on a bus as high as 400 V using an I2C- or SMBUS-compatible interface. This design is targeted towards industrial applications where there is a need to measure system current accurately with bus voltages greater than 40 Volts such as Solar inverters, HEV/EV systems and Source generation for AC/DC electronic loads and power sources.

For the design to sense current, it takes advantage of the INA226. The INA226 is a current shunt and power monitor with an I2C™- or SMBUS-compatible interface. The device monitors both a shunt voltage drop and bus voltage. Programmable calibration value, conversion times and averaging, combined with an internal multiplier enable direct readouts of current in Amperes and power in Watts. The INA226 senses current on common-mode bus voltages that can vary from 0 V to 36 V, independent of the supply voltage.

For current amplification, the design uses a OPA333. The OPA333 series of CMOS operational amplifiers use a proprietary auto-calibration technique to simultaneously provide very low offset voltage (10 µV, max) and near-zero drift over time and temperature. These miniature, high-precision, low quiescent current amplifiers offer high-impedance inputs that have a common-mode range 100 mV beyond the rails, and rail-to-rail output that swings within 50 mV of the rails. Single or dual supplies as low as +1.8 V (±0.9 V) and up to +5.5 V (±2.75 V) can be used. These devices are optimized for low voltage, single-supply operation. The TIDA-00528's block diagram is seen in Figure 4.21.

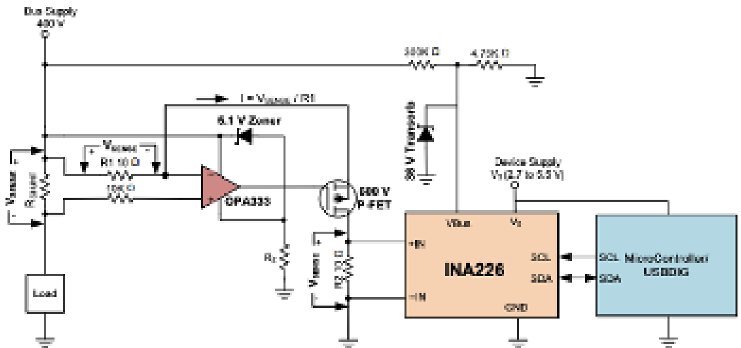

Figure 4.21. TIDA-00528 Block Diagram

The OPA333 is used to mirror the sense voltage across the shunt resistor on to a precision resistor R1. OPA333 is floated up to 400 V using a 5.1 V Zener diode between its supply pins.

This design also does not use an ADC incorporated on PCB but uses an external one that would be placed on the board. Table 4.6 summarizes the TIDA-00528's specifications.

Table 4.6 TIDA-00528 Voltage Sensing Specifications

PARAMETER	SPECIFICATIONS and FEATURES
Operating Bus Voltage range	40 V to 400 V
Operating temperature	+25 °C
Wired Interface from Current Shunt to Application Processor	I^2C Compatible
Accuracy at Full scale	<1%
Form Factor	67.8 mm x 93 mm square PCB

TIDA-01063: The TIDA-01063 is a reference design for current sensing using a PCB Rogowski coil sensor to achieve very good linearity for wide measurement range at a very low system BOM cost. The PCB Rogowski sensor is advantageous for isolated current measurement due to its very high bandwidth of 20 MHz and fast settling time of 50 ns. The auto-zeroing, 12-nV/√Hz noise density of the INA188 makes it suitable to achieve a 12-bit system resolution for a full-scale current of 1000 A.

A three-phase AC induction motor drive system has a feedback sensor for current, speed, and rotation sensing, all integral parts for motor protection and motor drive systems. For better system accuracy and stability, sensors need to be linear and highly accurate. The design uses the INA188. The INA188 is a precision instrumentation amplifier that uses TI proprietary auto-zeroing techniques to achieve low offset voltage, near-zero offset and gain drift, excellent linearity, and exceptionally low-noise density that extends down to DC. The INA188 is optimized to provide excellent common-mode rejection of greater than 104 dB.

Our design also uses the LP5907. The LP5907 is a linear regulator capable of supplying a 250-mA output current. Designed to meet the requirements of analog circuits, the LP5907 provides low noise, high PSRR, low quiescent current, and low line or load transient response figures. The LP5907 offers class-leading noise performance without a noise bypass capacitor and the ability to place remote output capacitors.
To supply power to the IC's it uses the LM2776. The LM2776 CMOS charge-pump voltage converter inverts a positive voltage in the range of 2.7 to 5.5 V to the corresponding negative voltage. The LM2776 uses three low-cost capacitors to provide 200 mA of output current without the cost, size, and electromagnetic interference (EMI) related to inductor-based converters. It also uses the REF2025. The REF2025 offers excellent temperature drift (8 ppm/°C, max) and initial accuracy (0.05%) on both the VREF and VBIAS outputs while operating at a quiescent current of less than 430 µA. In addition, the VREF and VBIAS outputs track each other with a precision of 6 ppm/°C (max) across a temperature range of –40°C to 85°C. All these features increase the precision of the signal chain and decrease board space while reducing the cost of the system as compared to a discrete solution. The TIDA-01063's block diagram is seen in Figure 4.22.

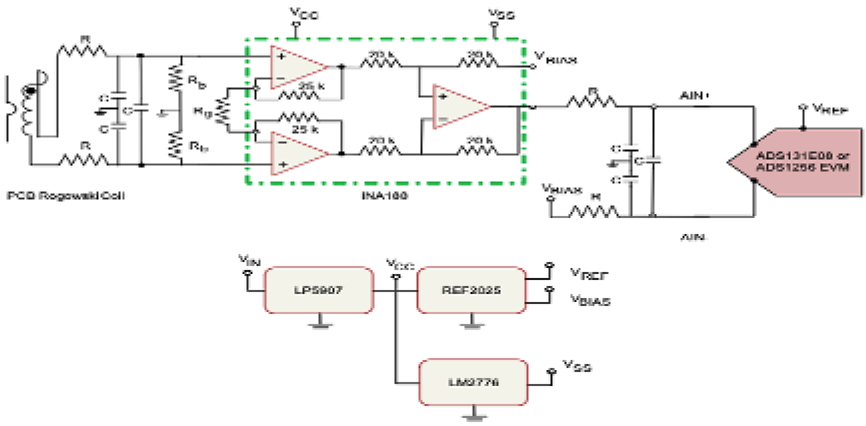

Figure 4.22. TIDA-01063 Block Diagram

TIDA-00640: The TIDA-00640 verified reference design provides an overview on how to implement a solar module level monitoring and communication sub-system. This design addresses the key need of a highly cost optimized monitoring and communication sub-system for solar Module Level Power Electronics (MLPE). This design showcases a highly integrated solution for accurate voltage, current and temperature monitoring along with ZigBee communication using CC2538 to enable Solar Module level monitoring.

To measure current, a low-value current shunt resistor was chosen as the sensor in this TI Design to keep system complexity and cost to a minimum. This design uses a low-side sense element to reduce the need for high-voltage translation typical of a high-side element. The TIDA-00640 uses the built-in ADC on the CC2538 for measurement.

For the voltage, The TIDA-00640 uses a simple voltage divider and amplifier configuration to measure the module level voltage. A low upper limit was set to give the analog circuitry plenty of overhead in the case of higher-than-expected module voltage output. The voltage sensing divider feeds a simple buffer amplifier, which shares a package with the current sensing amplifier. As in the current measurement system, a VREF of 3.3 will be used on the ADC of the CC2538. The current sense amplifier is the TLV342A that we made mention of earlier. The ADC used is the CC2538, which uses the Zigbee communication protocol. LM5017 is used to supply 3.3v to the IC's. Since the voltage coming from the solar panel will be too high for the IC's, the LM5017, since it is a buck converter, would step down the incoming voltage to the desired amount and then sends that voltage instead.

Table 4.7 summarizes the specifications of the TIDA-00640

Table 4.7: The TIDA-00640's Sensing Specifications

PARAMETER	SPECIFICATIONS
Voltage Input	10- to 90-V input voltage support for modern HV modules
Sensor type	Shunt resistor
Current measurement accuracy	<2% calibrated and uncalibrated error full scale
Voltage measurement accuracy	<2% calibrated and <2.5% uncalibrated error full scale
Temperature measurement	±5°C
Wireless functionality	1 minute of no motion detected

For the All-in-one PV sensor, we would use the TIDA-00640 as our reference design. The design contained the necessary parts needed for our sensor. We would need to modify the design because the TIDA-00640 assumes the solar panel outputs 90v. Also, the TIDA-00640 was used for a solar panel which is a perfect fit for our All-in-one PV sensor, so since the design showed promising results, it allows us to keep our minds at ease when we use the design.
For the current and voltage sensing, we would be using a component that contains two op amps, and two different configurations would be used for both

They are linear devices that have all the properties required for nearly ideal DC amplification and are therefore used extensively in signal conditioning, filtering or to perform mathematical operations such as add, subtract, integration and differentiation.

For our current sensing, we would be using the non-inverting op-amp configuration. In this configuration, the input voltage signal, (V_{IN}) is applied directly to the non-inverting (+) input terminal which means that the output gain of the amplifier becomes "Positive" in value in contrast to the "Inverting Amplifier" circuit we saw in the last tutorial whose output gain is negative in value. The result of this is that the output signal is "in-phase" with the input signal.

The voltage coming from the shunt would be a very small value, this would be what the ADC would measure, but the voltage would be too small. The op-amp would amplify the signal with a certain gain determined by the resistors, then it would send it to the ADC.

For voltage sensing, a voltage follower would be used. If we made the feedback resistor, Rf equal to zero, ($Rf = 0$), and resistor R2 equal to infinity, ($R2 = \infty$), then the resulting circuit would have a fixed gain of "1" (unity) as all the output voltage is fed back to the inverting input terminal (negative feedback). This configuration would produce a special type of the non-inverting amplifier circuit called a **Voltage Follower**, also known as a "unity gain buffer".

As the input signal is connected directly to the non-inverting input of the amplifier the output signal is not inverted resulting in the output voltage being equal to the input voltage, thus Vout = Vin. This principle would be how the voltage is measured. The voltage divider would reduce the voltage coming out of the solar panel, then the unity gain buffer would send the voltage to the ADC. This Unity buffer also helps to reduce power consumption since very little current would be used.

4.3.5 TEMPERATURE SENSOR

As seen in the previous sections the reference designs for the Temperature Sensor, after carefully consideration, we opted to select from the different types of thermocouples a Type T Thermocouple as provided by OUC for our prototype design and Type K for our design implementation. Meaning we need a more optimized design that it would work with a Type K or Type T. Furthermore, one of the main specifications by OUC is that the sensing node or “All in One PV Sensor” needs to be available work without having one of the two external sensors connected. Therefore, the design should accommodate a detection circuit where it can detect when the circuit is open.

One of the design constraints for successfully implanting a thermocouple with the ESP32 is that it requires us to make a conditioning circuit that will create the necessary conditions for the ESP32 ADC to detect the minimum analog signal voltage to operate properly. One of the main components for the conditioning circuit any one the previous designs as the addition to a cold junction compensator only necessary for a Type K thermistor. This can be accomplished by two various methods one is an ice bath that reaches 0 degrees Celsius, another is adding a second temperature sensor that monitors the temperature in the cold junction to then compensated.

The most efficient method with an acceptable percentage of error is a hardware cold junction compensator talked more in depth in the fallowing section. In short, the two most popular methods to accomplish this compensation in a small profile design is the used of an isothermal block made from a high temperature conducive metal where it can easily reach room temperature where you can connect a thermistor so then we can later then subtract the difference between the Hot Junction known as the tip of the thermocouple and the Cold Junction.

The main drawback of using a thermocouple is that it produces a small amount of voltage typically in millivolts which is usually a small amount of voltage that a typical Analog to Digital (A/D) will not be available convert the signal properly. Therefore, we will need to design an amplifier circuit that can multiply the signal for the A/D to successfully convert the voltage signal as seen in Figure 4.23. The Temperature Sensor Amplification and Filtering. In addition to an amplifier circuit the design will also need to incorporate a decoupling capacitor to filter out the noise from the voltage source for the signal conditioning circuit.

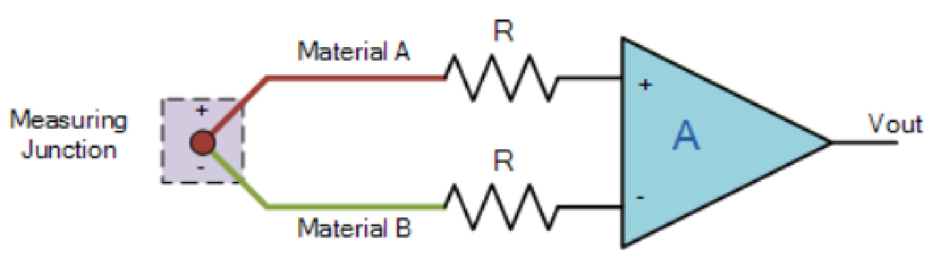

Figure 4.23. Thermocouple Amplification

As seen in the Table 4.8 below we can clearly compare the temperature range we will need for our all-in-one PV sensor. In our specifications we concluded that the Temperature range we need to measure which a typical solar panel can reach is between 15 ºC to 65 ºC in Florida [4.17]. If carefully consider all the different types of temperature sensors we can conclude that the best and most cost-effective temperature sensor for our application is a Thermocouple. Not only it provides a cost-effective solution it has a wide range of sensitivity within the temperature range of 15 ºC to 65 ºC.

Table 4.8: Types of Thermocouples with Specifications

Type	**J**	**N**	**U**	**T**	**E**	**K**
Component #	FF-J-20-25	GG-N-20-25	XE-2500	FF-T-20-25	FF-E-20-25	FF-K-20-25
Conductor Type:	Solid	Solid	Braided	Solid	Solid	Solid
Temperature Range:	0ºC to 200 ºC	0ºC to 260 ºC	-10ºC to 105 ºC	0ºC to 200 ºC	0ºC to 200 ºC	0ºC to 200 ºC
Wire Gauge:	20 AWG	20 AWG	20 AWG	20 AWG	20 AWG	20 AWG

Furthermore, as noted previously, we will use a contact thermocouple some comparisons between then can be found in Table 4.9. Another benefit of using a thermocouple is that it has a fast respond time when there is a fluctional of temperature giving us the ability to have a high sample rate from where we can send this data to the main node

Table 4.9: Temperature Sensor Comparison

Temperature Sensor:	Thermistor	Thermocouple T Type	RTD
Component #	10K Precision Epoxy Thermistor - 3950 NTC	FF-T-20-25	TFD-ENB-2W-40
Resistance:	10kΩ	-	100Ω
Temperature Range:	-55 ºC to 125 ºC	0ºC to 200 ºC	-50 ºC to 550 ºC
Wire Gauge:	28 AWG PVC Wire	20 AWG	-
Cost $:	$4.00	$36.56	$97.30

Cost $:	$49.88	$56.14	$13.15	$36.56	$61.56	$54.45

.
As seen in Figure 4.24 we and in our previous reference design to property analyze the analog signal coming from the thermocouple we need is a conditioning circuit added to our amplifier circuit to have a voltage difference between our Cold Junction reference node to our Hot Junction tip of the thermocouple.

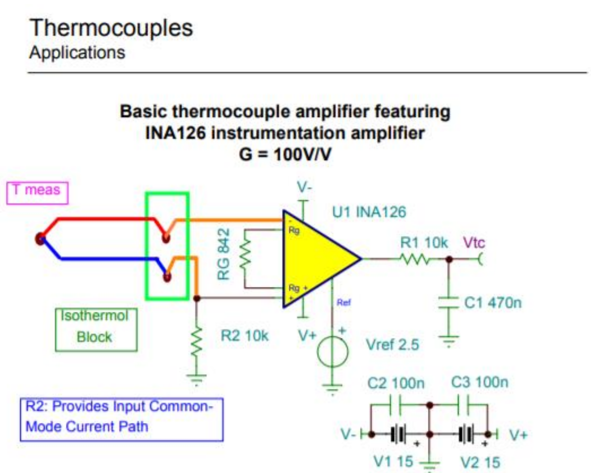

Figure 4.24.5 Amplifier with No compensator

As seen in Figure 4.25 this design features an Isothermal block to act as our part of our conditioning circuit where we will connect an 1N4148 to monitor its temperature and reference the voltage from that reference node so that in the code we can subtract the reference voltage by the output voltage of the amplified voltage giving us a more accurate voltage reding for our conversion equation. However, this design does not accommodate for open circuit detection which can make our data unstable since it will show random values for an open circuit.

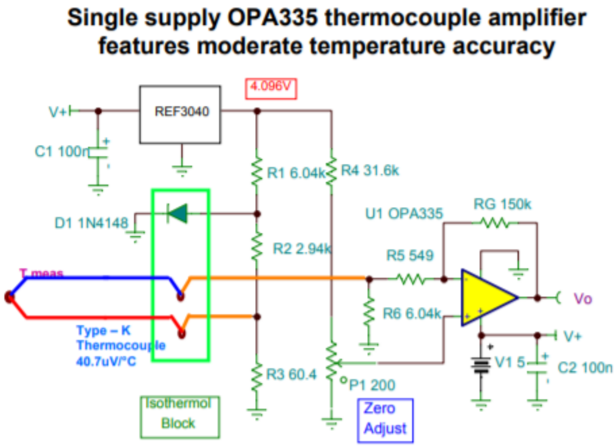

Figure 4.25. Amplifier with Compensator

As we analyze potential reference designs, we keep encountering cold junction compensation and signal voltage amplification in our reference designs. This means that to implement our design correctly for our ADC and microcontroller to interpret the signal correctly we must first condition our signal voltage to a suitable voltage that our ADC and microcontroller can detect an analyze for this reason we must use a conditioning circuit or also known as signal conditioning to transform our voltage signal to a suitable one for our ESP32 to detect.

The two most important factors we need to understand to implement our conditioning circuit is how do we compensate for our cold junction on our thermocouple to read the appropriate voltage according to the manufacturers expected voltage according to temperature.

The second one is that a thermocouple produces small amounts of voltage produced by a temperature difference between the Hot and Cold junction giving us a small but predictable mV reading. Therefore, since we have a mV output voltage we must amplified this to around 3.3 volts which is the range for detectable voltage reading on our ESP32.

If we zoom in in the internal composition of the MAX6675ISA chip as seen in Figure x, we can clearly see this specialized chip has a built-in internal cold junction compensator as well a low-noise amplifier. For the built-in cold junction compensator instead of using an isothermal block to monitor the temperature at the base of the thermocouple for the temperature conversion it instead uses a sensing diode.

This sensing diode with its internal circuitry it can sense the ambient temperature of its surroundings in this case the based or cold junction of the thermocouple insuring a more accurate temperature reading. Since we know the temperature difference from the hot junction and the cold junction of the thermocouple, we can the proceed to use the linear voltage equation to convert our voltage difference between our Hot Junction temperature voltage and cold junction ambient temperature voltage to get our actual voltage output that will be send to our ADC.

As we procced to the ADC the main function as seen in Figure X is to add the call junction dial measurement with the amplified thermocouple voltage which then converts it to a 12-bit resolution which in this case is 3.3 volts divided by 2^{12} which give us a 0.805mV ADC resolution which is within a reasonable temperature sensitivity well below 5% temperature discrepancy limit given by our client constraints.

In the Figure 4.26, it can be seen that this design does not only accommodate a cold junction compensation it also has a open circuit detection that detects if the thermocouple is connected or not turning off the amplifier so it does not produce a voltage with empty terminal due to low voltage noise.

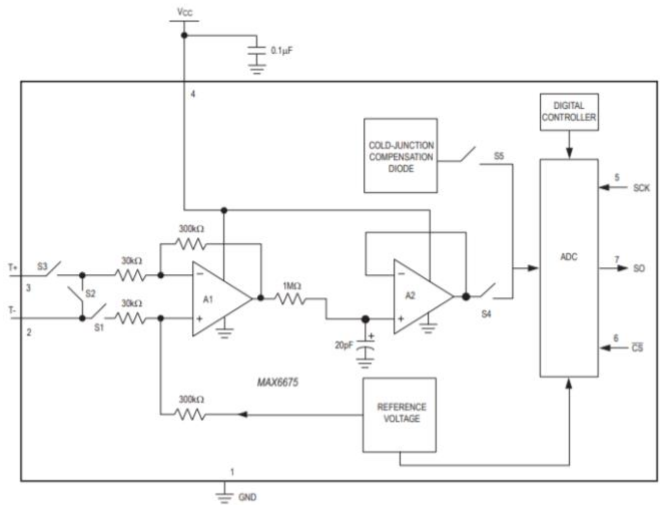

Figure 4.26. Open Circuit detection thermocouple amplifier

4.3.6 IRRADIANCE SENSOR

A pyranometer is a device that can sense and measure solar irradiance. More specifically, a pyranometer measures the amount of solar energy over an area and over time on a usually flat surface. For the All-In-One PV sensor, the pyranometer will be used to understand how much light a panel is receiving. If a panel is underperforming, the pyranometer would be able to show whether the panel's exposure to light could possibly be the issue – if the pyranometer is detecting normal levels of irradiance while a panel is not, the panel could be obscured or damaged.

Pyranometers do not simply detect the amount of light that is shining on it; a pyranometer is also able to account for the angle of solar radiation by employing the use of either a diffusor or a glass dome when sensing. The pyranometer can operate based on a difference in temperatures between two surfaces, one clear and one black.

Pyranometer Technologies

There are two main pyranometer technologies: thermopile pyranometers and silicon semiconductor pyranometers. Thermopile pyranometers are based on thermopiles which convert thermal energy into electrical energy. Thermal differences are measured across the two surfaces and the radiation intensity is found to be proportional to the temperature difference that the pyranometer senses. Because of this, thermopile pyranometers are much more accurate compared to its counterpart, the silicon semiconductor pyranometer. [4.18] Silicon semiconductor pyranometers usually depend on photo-sensitive diodes which are in proportion to solar intensity. The photodiode converts this solar spectrum into a current and that current reflects the amount of irradiance that the pyranometer is measuring.

Pyranometer Constraints

For the creation of the All-In-One PV Sensor, the sensing circuit should be drawing little to no power from the generation of the solar panels. This means that the pyranometer must be self-powered or supplied with a supplementary battery or power generation source outside of the pyranometer. The pyranometer must also be able to connect to the PCB to be a part of the All-In-One PV Sensor, not a supplementary device.

Not all of the created All-In-One PV Sensors will require the pyranometer; if a solar farm has multiple panels adjacent to one another, it's likely that they will all be receiving the same irradiance and the need for more than one pyranometer is unnecessary. Because of this, the cost is not as important of a factor.

Pyranometer Considerations

Because this is a research project, a Class C pyranometer will be used due to its comparatively lower cost. Additionally, certain pyranometers will not be considered due to their inability to connect directly to a PCB without intervention. There exist several commercially available pyranometers of every class, and for this project the following have been considered.

SP-110-SS Self-Powered Pyranometer: This pyranometer offered by Apogee Instruments was given to the team directly from the sponsor, OUC. The pyranometer is fully self-powered through its incorporation of a silicon-cell photodiode and features pre-tinned pigtail leads to easily connect to a PCB for datalogging. This sensor has a response time of less than one millisecond which is much higher than Class C expects from its pyranometers. This sensor was selected by the previous team for all of its qualities listed thus far and will likely be re-employed for the final All-In-One PV Sensor Design. This sensor usually costs $223 per pyranometer, $299 from Alphaomega Electronics. [4.19][4.20]

SP-510-SS Thermopile Pyranometer: This pyranometer is also offered by Apogee Instruments but does not incorporate silicon-cell photodiodes. This thermopile has a much higher response time of around 0.5 seconds with the benefit of about half of the error compared to the SP-110-SS Pyranometer. This pyranometer also features pigtail-lead wires to easily connect to a PCB but appears to be lacking any additional functionality compared to the SP-110-SS Pyranometer offered at a cheaper price, as this sensor can cost $333 per pyranometer. [4.19][4.20]

CS320 Digital Thermopile Pyranometer: This pyranometer offered by Campbell Scientific combines a blackbody thermopile detector with an acrylic diffuser, offering a significant improvement compared to the spectral responses of silicon-cell photodiode pyranometers with a comparable price-point. In addition to this, the pyranometer naturally offers a higher accuracy due to being thermopile. However, this pyranometer requires an input voltage of 6 to 24 V, DC to operate. Interestingly, this pyranometer returns its findings in a digital format using SDI-12 functionalities. [4.21]

The findings are summarized in Table 4.10.

Table 4.10: Summary of Considered Pyranometers

Pyranometer	SP-110-SS	SP-510-SS	CS320
Technology	Silicon-Cell	Thermopile	Thermopile
Output	Analog, ~100mV	Analog, ~400mV	Digital
Power Supply	Self-Powered	Self-Powered	6~24 V, DC
Response Time	< 1 millisecond	~ 0.5 seconds	2 second SDI response
Price	~$230	~$330	~$524

For this project, it is likely that the team will continue to use the SP-110-SS Self Powered Pyranometer due to its comparatively low cost, lightweight design, and pre-tinned leads to connect itself to the PCB.

External Research of Pyranometer Implementations

It is beneficial to research any other existing implementations of a pyranometer in similar applications for comparisons. Doing so will enable the team to implement the pyranometer in the most efficient and cost-effective matter by consulting the thought processes of other like-minded researchers who have created projects with a similar scope.

One such implementation was created by Wichit Sirichote who aimed to implement a DC amplifier for a Pyranometer with an output of 14 uV/W/m^2 [4.22]. The analog input of a created data logger accepted +/-400 mV with a 100uV sensitivity, so Sirichote aimed to use a DC amplifier to provide a DC gain for the output of the pyranometer to increase it from 14uV to 100uV to send toward the data logger. For this, Sirichote used the INA101, a High Accuracy Instrumentation Amplifier due to the extremely small voltages that were in use.

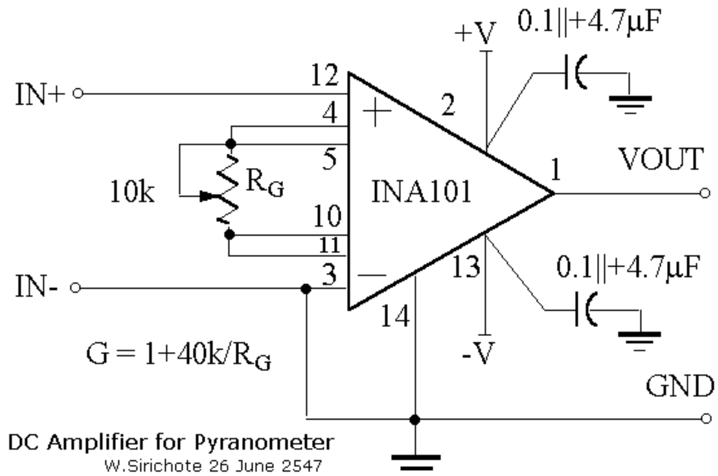

Figure 4.27. Sirichote's implementation of the INA101 DIP Package

In Figure 4.27, Sirichote connects RG to pins 4, 5, 10, and 11 for a DC gain adjustment and includes 4.7 uF decoupling capacitors at +V and -V. The output V_{out} is tied to the input of their local data logging device and the inputs at IN+ and IN- come from the pyranometer. The gain equation for the INA101 is

$$G = 1 + \frac{40{,}000}{R_G}$$

and given that RG is 10,000, the gain provided by this amplifier is 5 producing a final input of 70 uV/W/m^2 to the data logger, assuming everything that Sirichote described is correct. This proves to be a good implementation for a pyranometer for connection to a data logger and could potentially be remodeled to fit our project's needs.

Referring to the INA101's datasheet [4.23], the input voltage noise that it permits is typically 0.8 uV, peak-to-peak. Using the decoupling capacitors, it's likely that this configuration with a modified gain would be a good addition to the All-In-One PV Sensor.

Pyranometer Implementation – Apogee's SP-110-SS

It is mostly assumed that this project will move forward with the Apogee SP-110-SS Self-Powered Silicon Cell pyranometer for irradiance measuring. While earlier sections had made assumptions about the pyranometer's operation, most cannot be held true in the real world. For example, there will always be noise surrounding the pyranometer's output signal. For this reason, we will have to take steps to reduce the noise output by the pyranometer and attempt to clean the signal before it reaches the on-board ADC.

This section will cover several outlooks and their considerations, mainly low-noise operational amplifiers for boosting the output signals magnitude. First, Instrumentation Amplifiers will be considered. Instrumentation Amplifiers are a type of differential amplifiers that have inner input buffer amplifiers, eliminating the need for input impedance matching which in turn makes them incredibly useful for measurement applications such as ours. Because the amplifiers that we are interested in must be low-noise and capable of operating successfully at small voltages, the prices will be high in comparison to the rest of the board's components. Most researched instrumentation amplifiers require an input voltage that falls within a range of its supply voltage and must be considered.

INA333 [4.24]: The INA333 is a lower-power precision instrumentation amplifier that offers excellent accuracy with a relatively low noise of 50 nV per square root hertz at gains over 100. This amplifier is especially interesting due to its analog input voltage; the INA333 can take a maximum of 0.3V difference from its supply voltage. In addition to this, the INA333 can provide a gain of anywhere between 1 and 1000, giving the potential output of the amplifier a large range of variety. This gain is determined by the value of only a single external resistor, making the gain highly customizable and easily accessible. A single INA333 rests at around $6 per amplifier.

INA849 [4.25]: From a similar line of products, the INA849 is an ultra-low-noise instrumentation amplifier, offering a comparable 1 nV per square root hertz compared to the INA333's 50 nV. This amplifier has a larger range of input voltage taking up to a 0.5 V difference from its supply voltage, giving us more room to adjust. The INA849 also offers a larger range of possible gains, going up to 10000 V/V also controlled by a single eternal resistance with varying gain error percentages, all within 1% of its intended value.

INA126 [4.26]: The INA126 is advertised as a "great choice for … data acquisition systems" and that appears to be the case for our intended implementation. This instrumentation amplifier is low noise at 35 nV per square root hertz with an input range of 0.5 V difference from its supplying voltage. Similarly, to the previous two models discussed, this gain is controlled by a single external resistor. The INA126 is comparably cheaper than the previous parts sitting at about $4 per amplifier circuit. At a gain of 100, the error reaches 1% meaning that any specified gain below this value will provide an acceptable output.

The findings of this section are summarized in Table 4.11.

Table 4.11: Summary of considered Pyranometer Amplifiers

Instrumentation Amplifier	INA333	INA849	INA126
Input Voltage Range*	-0.3 Vs to +0.3 Vs	-0.5 Vs to +0.5 Vs	-0.5 Vs to +0.5 Vs
Gain Range	1-1,000 V/V	1-10,000 V/V	5-10,000 V/V
Noise	50 nV/√Hz	1 nV/√Hz	35 nV/√Hz
Supply Voltage Range	1.8 V to 5.5 V	8 V to 36 V	1.35 V to 18 V
Price	$6	$11	$4

From these findings, the INA126 was selected as the best performing instrumentation amplifier of the 3 choices. Its low cost and high input voltage range allows us to easily implement it to the board. In addition to this, it supports a single-supply power of 3.3V which matches closely with all other components on the board thus far. If the pyranometer is to be input to the INA126 with a baseline gain of 5, the resulting circuit can be found in Figure 4.28.

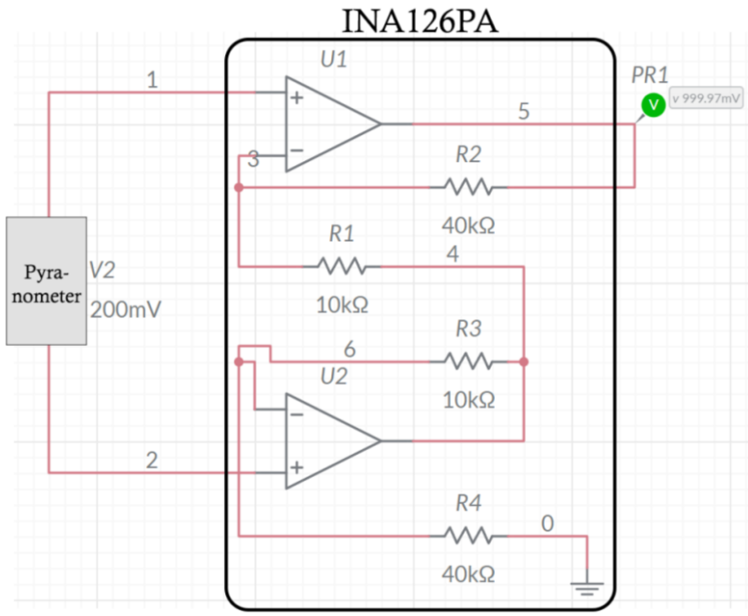

Figure 4.28. Pyranometer implementation using INA126PA

Now, at an expected maximum output of 200 mV from the SP-110-SS, we are seeing a 1V output from the Instrumentation Amplifier. With a gain of 5, this changes the pyranometer's output to 1 mV per 1 W per meter squared, allowing for a much easier conversion rate at the ESP32's ADC and increased resolution between comparable voltage values.

4.3.7 On-Board Component Power Supply

Power Supply

Power supply is a device that can provide electric energy to another electrical device. It is to convert one form of electrical signal to another such as DC to DC signals or DC to AC signals and vice versa. As constraint from the customer, our design must be powered by the solar panel which is producing an average of 35-volt DC. In order to maintain this request, our device should carry a power supply that can have a range of 32-to-40-volt DC as input. The consideration of that range is due to some external factors that can create some variation to the power given by the solar system yet to the output voltage of the PV cells. One of the main factors that can affect the voltage of the solar system is the temperature by fluctuation of the sunlight. That fluctuation of the sun can provide more or less power for the PV cells. For this reason, we can choose 40V as the maximum input voltage for our power supply.

Another consideration for the All-In-One PV sensor is that the power supply output voltage can be also chosen in a way to suit other components because it will be comprised with other internal circuits that require an input voltage to be on. The range for this output voltage can be varied from 2.7-to-5-volt DC. The design is an interconnection between components, one component can supply energy to another one and they are all low power elements mean that they don't consume much energy. A maximum output voltage DC supply of 5 volts is enough to energize the device system.

By looking for power supply, voltage regulator is important factor for our design. voltage regulator is to take the input voltage and then to convert it to another and the output voltage that can be a constant for wide range for input voltage especially for DC-DC converter. From this perspective, our goal is to focus on the way how to select what type of regulator that can be best fit our design. Therefore, there are two types of regulators can come into consideration: linear and switching regulators.

Linear Regulator

Linear regulators can be described as a simple design configuration where it could be used to step-down voltages. It appears as very good choice in term of simplicity, it is a very low power device with low noise, and it is also cheaper. Some of the disadvantages of this device are it can only step- down the output DC voltage and it is inefficient because of its power dissipation.

Types of Linear Regulators

There are different types of linear regulators, but the most common one is the low dropout regulator. The configuration of this type of regulator is made with a PNP transistor also called LDO. The interesting feature about this regulator is it can maintain the regulation voltage at very low level and the maximum current can flowing through transistor is about 0.6 to 0.7 A. other types are standards, they can regulate the output voltage either positive or negative.

We can observe that the input current is the same as the output current because of the input power is not doing any work just producing heat to the regulator. In other terms, it is creating a power loss or dissipated and making the system inefficient by having the output much less than the input voltage. because of that a such of device cannot be considered for our design. we don't want to put an excess heat on the system that can affect the proper functioning of other components. A typical linear regulator is shown in Figure 4.29.

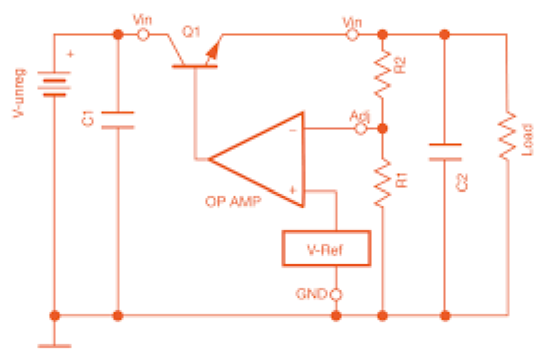

Figure 4.29. A typical Linear Regulator configuration

Switching Regulator

Switching regulator also known as switched mode power supply (SMPS) is another type of regulator converter of voltage. In contrast to linear regulator, switching regulator is much more efficient and more reliable in terms of modulation availability, complexity and compacity. They can be either step-up or step-down. It is using a temporary storage energy and after to release that power to the output voltage with different value. The way it works is when the transistor is on there is current flowing with low voltage.

When the transistor is off there is no current and any high voltage is block at this point it behaves as an ideal switch. Those switching regulators come with different types: buck (step-down), boost (step-up), and buck/boost (step-down/up) switching regulators. Figure 4.30 is a typical switching regulator.

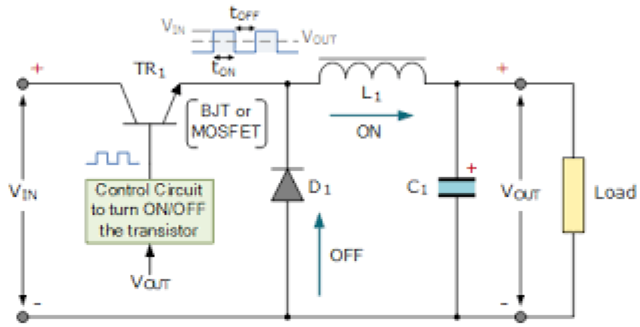

Figure 4.30. A basic Switching Regulator Configuration

<u>Buck Regulator</u>

It is to step-down the voltage regulators mean that is to take a high input voltage and then transform it to a lower one as output voltage. it works similarly to a linear regulator only exception is that it has better efficiency and has less power dissipation.

<u>Boost Regulator</u>

It is to step-up the voltage regulators. In contrast to buck regulators and linear regulators, it takes a low input voltage and converts it to a higher output voltage. this type of regulators works differently compared to linear regulators and buck regulators because of the configuration that allows a greater output voltage than the input.

<u>*Buck/ Boost Regulator*</u>

Another type of regulator is buck/boost regulator, this is a combination of buck converter and boost converter. It works in both ways by step-down or step-up the voltage regulator with a large range of the input voltage, the output can be more or less than the input voltage.

Table 4.12 summarizes the difference between the linear and the switching regulators.

Table 4.12: Comparison of Linear and Switching Regulators

	Linear regulator	**Switching regulator**
Efficiency	Low (typically 60% to 70%)	High (typically 95%)
Control method	Passive or active an op amp	**PWM signal**
Polarity	Same as input voltage	Reversible
Scaling	Step-down	Step-up or step-down
Max. voltage output	Low	Moderate to high
PSRR	Broadband, up to ~70 dB depending on frequency	~50 to 100 dB, depending on frequency
Noise	Low frequency noise that matches input ripple	- 10-1,000 kHz noise due to the PWM signal and switching. - Ripple on the output.

Maximum Power Point Tracking (MPPT)

When designing it is still important to address the concept of efficiency to improve the quality of the device. In this section, we still need to investigate how we can implement our device much better. For this reason, we want to compare the quality of the elements we want to integrate in our project. It is necessary to know that when it's appropriate to use a PWM or a MPPT. At first it seems like PWM can be the best choice, but after research it shows that MPPT has more advantages that PWM. To illustrate let see what it has been studied.

We already illustrate some of the characteristics of linear regulator and switching regulator as a Pulse Width Modulation (PWM). As we mention before linear regulator is prized for its simplicity, it is cheap compared to switching regulator, has low noise, but its power dissipation is very high. For switching regulator on its side, it has a small dimension, high efficiency greater than 90% and it can allow several output ranges. On the order hand, switching regulator sometimes uses inductor coils that can cause EMI interface which can end up to high frequency noise. In addition, this is a complex design, and it is relatively expensive.

Now we want to introduce the Maximum Power Point Tracking (MPPT). It becomes as another constraint 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. 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. Figure 4.31 shows the block diagram of the TIDA-010042, and Table 4.13 shows some key system specifications of the TIDA-010042 MPPT.

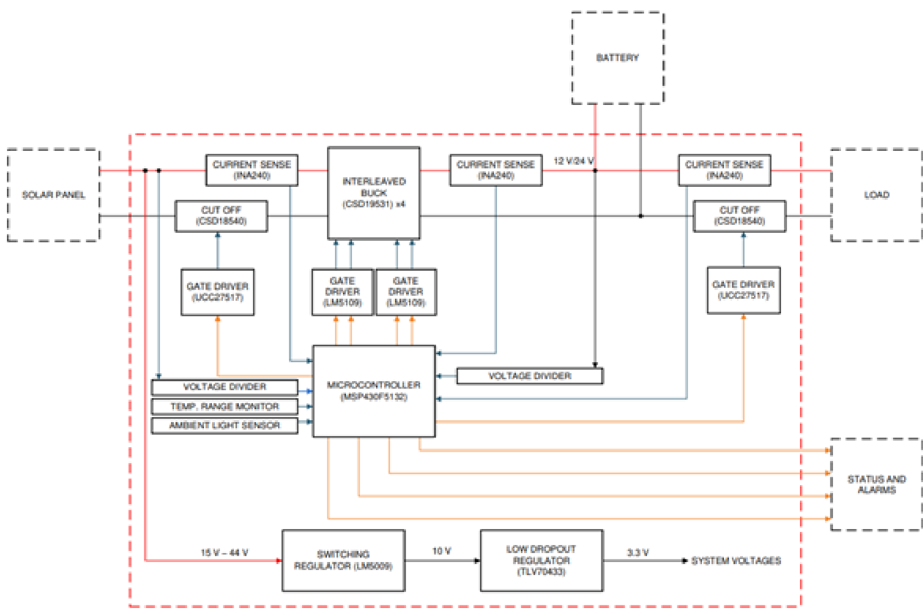

Figure 4.31. TIDA 010042 Block Diagram

Table 4.13: TIDA-010042 MPPT 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

4.3.8 Communication Protocols

A crucial component of this project is data transfer. As our device will be located on-board solar panels, variably distant from our receiver node, we must utilize wireless data transfer to communicate between our collector nodes and receiver node. There are many forms of wireless communication but there are two methods of wireless communication that are the most applicable and practical for our device. We will discuss Wi-Fi and Bluetooth wireless network protocols.

Wi-Fi

The IEEE 802.11 family of standards is commonly used for wireless networking. It allows nearby devices to receive and exchange data using radio waves. Wi-Fi is also widely used in public areas such as coffee shops, hotels, and airports to provide Internet access to mobile devices.

The Wi-Fi Alliance is a non-profit organization that carries out interoperability testing and certification of Wi-Fi-capable devices. As of 2019, more than 3.05 billion Wi-Fi-capable devices are sold globally. Wi-Fi is a wireless networking technology that works seamlessly with the IEEE 802 protocol family. It can connect various devices, such as mobile platforms and the Internet, through a network of access points. The various versions of the Wi-Fi standard vary in terms of radio frequency and speeds. Wi-Fi most commonly uses the 5 gigahertz and 2.4 gigahertz radio bands. These bands are divided into multiple channels.

Wavebands of Wi-Fi are relatively high-absorption and work well for line-of-sight use. Although they can reduce range due to the presence of walls and other obstacles, they can still provide a good distance between different networks. Covering areas that are small to large can be achieved using multiple access points and walls. As of 2019, some Wi-Fi devices can reach speeds of up to 9.6 Gigabits per second. The IEEE doesn't test equipment for conformance with its standards. To address this issue, the Wi-Fi Alliance was established in 1999. Through its membership, over 800 companies have signed up to the organization.

The Wi-Fi Alliance is responsible for enforcing the use of the Wi-Fi brand across various technologies. Some of these include 3Com, Aironet, and Harris Semiconductor. Members of the Wi-Fi Alliance are granted the right to mark their products with the Wi-Fi logo. The certification process involves testing and conformance to various standards, such as the IEEE 802.11 radio standards and the WPA and EAP2 security protocols. Although not every Wi-Fi device is certified, the lack of certification does not imply that the network technology is incompatible with other devices.

To use Wi-Fi, devices must first communicate with a common version. The version they use has various features and characteristics that can allow them to support different data rates and provide better connectivity. Since the beginning of 2018, the devices have been displaying the version of Wi-Fi that they support. These new generations, which are backward compatible with older versions, can now be connected to the device's UI. The easiest way to identify the version that's supported is by the number 4 or 5 in the list. The list of the most popular versions of Wi-Fi is as follows: 802.11a, 802.11b, 802.11g, and 802.11n. Table 4.14 below includes all versions of Wi-Fi.

Table 4.14: Wi-Fi Generations

Generation	IEEE Standard	Maximum Bitrate (Mbit/s)	Adopted	Radio Frequency (GHz)
Wi-Fi 6E	802.11ax	600 to 9608	2020	6
Wi-Fi 6	802.11ax	600 to 9608	2019	2.4/5
Wi-Fi 5	802.11ac	433 to 6933	2014	5
Wi-Fi 4	802.11n	72 to 600	2008	2.4/5
Wi-Fi 3	802.11g	6 to 54	2003	2.4
Wi-Fi 2	802.11a	6 to 54	1999	5
Wi-Fi 1	802.11b	1 to 11	1999	2.4
Wi-Fi 0	802.11	1 to 2	1997	2.4

Wi-Fi stations send and receive data packets individually over radio. They do it through a method known as demodulation and modulation. The differences between the different versions of the technology are reflected in the different carriers used in each version. Like with other 802 LANs, the addresses of each Wi-Fi station are printed on the equipment's labels. These addresses are used to specify the destination and the source of the data packet. The destination address of a packet is used by the receiver to determine if the connection is relevant to the station.

Wi-Fi communication channels are typically half duplex and can be time-shared among multiple networks. When two or more devices are connected to the same channel, all the information sent by one of them is sent to the other. This method of data sharing allows the devices to use the same network interface card. Collision avoidance (CSMA/CA) is a technique that prevents networks from colliding. It sends traffic only after the channel has been sensed to be idle.

The 802.11 standard has several radio frequencies ranges that can be used for Wi-Fi communications. These ranges are divided into various channels and are numbered from 5 MHz to 2.16 GHz. While the number of channels is limited to 5 MHz, transmitters can still occupy at least 20 MHz. In the US, 802.11b/g/n can use the 2.4 GHz band, which is considered Part 15 of the regulations. In contrast, Australia and Europe allow for the use of more channels than the 11 allowed in the US. In the US, however, devices that use the newer versions of Wi-Fi can only operate without a license. For most of the world, 802.11a/b/g/n can use the 5 GHz U-NII band, which has more channels than the 2.4 GHz band. The 5 GHz bands are absorbed better by common building materials and provide a shorter range.

As the technology evolved to support higher bandwidth, Wi-Fi protocols became more efficient in their use of available bandwidth. In addition, they can now combine multiple channels together to gain even more processing power. In addition, 802.11n can now also limit itself to 20 MHz to prevent interference in densely populated areas.

The data contained in a Wi-Fi network is organized into frames that are like Ethernet frames. The physical layer and the MAC of Wi-Fi are defined by the IEEE. These are the standards that are used by manufacturers to develop their products. The base version of the Wi-Fi standard was released in 1997. It contains numerous amendments that provide the basis for the creation of wireless network products. Aside from the IEEE 802, also known as the 802, also has specific requirements for Wi-Fi. This is because, unlike Ethernet, wireless communication media is prone to interference. Due to these requirements, the 802's Logical Link Control (LLC) uses Wi-Fi's media access control protocols to manage retries. It eliminates the need for higher levels of protocol stack.

For internetworking applications, Wi-Fi typically has a link layer that's below the Internet Protocol's layer. This means that it can provide full Internet access without overloading the network. Wi-Fi can be blocked if multiple devices are in the same area. To minimize interference, it uses Carrier-sense multiple access to prevent transmissions between devices. The number of channels in a Wi-Fi network is limited to five in the 2.4 GHz band. In addition, any two channels that are within the same band do not overlap each other. In North America, the three non-overlapping channels are the only ones that can be considered significant. However, if the two channels are more than a couple of meters apart, then the overlap is minimal. Unfortunately, many 2.4 GHz access points default to the same channel when connected to the same network. This causes congestion on certain channels and can affect the operation of other devices within the area.

Other devices such as security cameras, camcorders, and baby monitors use the 2.4 GHz band. Due to their wide variety of uses, this frequency can cause significant interference. Some 5 GHz bands can also be interfered with by radar systems. To prevent this, base stations that support these bands should implement a Dynamic Frequency Selection feature. Although unlicensed bands can be used by low-power transmitters, they can also be interfered with by unauthorized users. In most cases, these users have been issued large fines.

The IEEE 802.11 layer-2 has various characteristics. Some of these include maximum achievable throughputs that are calculated according to ideal conditions and data rates. However, this does not apply to most deployments where data is transferred between two devices that are typically connected to a wired network. The goal of this type of data rate is to provide a consistent and high-quality flow of data for an application. The main factors that contribute to this rate are the speed at which the packet is transmitted, and the energy used to transmit the signal. The distance and the power consumption of the devices are also known to affect the maximum throughput. The attached graph shows the average size of the packets, the size of the data rate, and the configuration power of the devices.

There are multiple modes of communicating through Wi-Fi as well, aside from the differing technologies in generations of Wi-Fi. Different modes of Wi-Fi involve the number of devices in which is involved in a single network. As depicted in Figure 4.32, infrastructure mode and ad hoc mode Wi-Fi are the two main modes that most Wi-Fi devices employ.

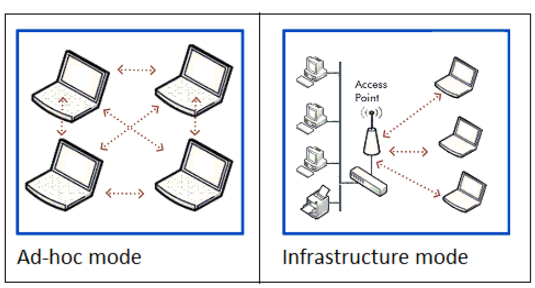

Figure 4.32. Ad-hoc mode vs. Infrastructure mode

In infrastructure mode, all communication between the network and its devices goes through a base station. This mode simplifies the protocols by allowing multiple devices to communicate with each other. Wi-Fi also allows devices to communicate without an access point. This is known as ad hoc transmission. This is also the mode that will be utilized in our devices to eliminate the need for an intermediate device. In most cases, network nodes must talk to each other to establish a connection.
In 1996, Chai Keong Toh of IBM introduced the concept of ad hoc routing using Lucent WaveLAN 802.11a wireless technology. His method was successfully implemented on IBM ThinkPads. This mode of wireless networking has become popular with various consumer electronics devices, such as the Nintendo DS and the PlayStation Portable. The Wi-Fi Alliance promotes the use of Wi-Fi for various applications. One example of this is the Wi-Fi Direct specification, which was launched in October 2010.

Bluetooth

Bluetooth is a wireless technology that is commonly found in many modern devices like smart phones and laptops. Bluetooth is a means of communicating data over short distances, usually in the range of 10 meters. Unlike Wi-Fi, Bluetooth is managed by a proprietary organization called Bluetooth Special Interest Group (SIG).

Bluetooth can operate at frequencies ranging from 2.402 to 2.480 GHz, and it includes guard bands 2 MHz wide. Bluetooth uses a radio technology known as frequency-hopping spread spectrum, which allows it to divide data into packets. It sends each packet to one of its 79 designated channels. Due to its 2 MHz spacing, Bluetooth Low Energy can support up to 40 channels. The only other option was the Gaussian frequency-shift keying scheme. Devices that use the GFSK algorithm can be expected to operate in the basic rate (BR) mode, where a bit rate of 1 Mbit/s is possible. They can also be operated in the enhanced data rate (EDR) mode, which provides 2 and 3 Mbits per second respectively. Each device in a piconet uses the clock provided by the master to exchange packets. The master clock has a duration of 312.5 s. When sending single-slot packets, the master sends and receives in even slots, while the slave uses odd slots. For long-distance transmissions, the master and the slave use the same frequency, but with different slots.

A master BR/EDR device can communicate with up to seven devices in a piconet, though not all devices can reach the maximum. The devices can also switch roles, with the slave becoming the master. The master chooses which slave to address, and typically, it switches between devices in a round-robin fashion. Being a slave of multiple masters is possible in scatternets. The exact behavior is still unclear.

Bluetooth is a standard component used for low-power wireless communication. It uses a radio network to transmit data, and it doesn't require visual line of sight to work. Range is a function that depends on the power-class of the Bluetooth device. Class 3, 2, and Class 1 are typically found in mobile devices, while Class 1 is for industrial use cases. For Class 1 and 2, the range is typically 20–30 meters, and the effective range is determined by the various factors that affect the quality of the link and the air conditions in between. Most Bluetooth applications are focused on indoor conditions, where weak signal quality and wall attenuation make the range significantly lower than the line-of-sight ranges of the devices. Sometimes, a Class 2 device can extend the data link's effective range by connecting to a Class 1 device with higher sensitivity and higher transmission power. This can be done in most cases depending on the application's requirements. Some devices can also allow up to 1 km of open field range between two similar devices. The Bluetooth core specification does not limit the range beyond 10 meters. Table 4.15 summarizes these classes.

Table 4.15: Ranges of Bluetooth devices by class

Class	Maximum permitted power		Typical range (m)
	(mW)	(dBm)	
1	100	20	~100
1.5	10	10	~20
2	2.5	4	~10
3	1	0	~1
4	0.5	-3	~0.5

A device must be compatible with the various features of Bluetooth to use it. A Bluetooth profile is typically used to describe an aspect of wireless communication that a device can perform. The Bluetooth profile is typically placed on top of the core specification and its optional additional protocols. It can use features specific to the core specification, but only if the profile is tied to that specific version. The profiles are typically used by device manufacturers to allow their devices to work seamlessly with Bluetooth. For the Low Energy stack, a special set of profiles is required. Each profile has its own options and parameters that are used to perform its task. There are countless profiles available such as file transfer profile, cordless phone telephony, human interface device profile, personal area network profiling, LAN access profile, and many more.

Bluetooth is commonly used in various products such as mobile phones, tablets, media players, and gaming consoles. Due to the wide variety of devices that use it, its interference is prone to interference. Bluetooth is a wireless technology that enables people to transfer data between devices that are near each other. It works by allowing devices to connect to each other and perform various tasks. Through its ability to advertise various services, Bluetooth devices make it easier to use.

<u>Bluetooth vs. Wi-Fi</u>

Both Wi-Fi and Bluetooth are used for various and similar applications. Bluetooth is a wireless network that is commonly used for mobile devices. It is a replacement for the traditional cable connection used for various applications. Aside from smartphones, it is also commonly used for home applications such as smart energy management. While Wi-Fi is typically an access point-oriented network, Bluetooth is more prevalent in terms of applications. It can be commonly used in simple setups where two devices only need to connect using a minimal configuration.

<u>MQTT</u>

MQTT (MQ telemetry transport) is a lightweight messaging protocol that enables network clients to distribute telemetry data in low-bandwidth environments. It was designed to work seamlessly with embedded systems. MQTT is a distributed protocol that enables wireless networks to connect to devices with a small code footprint. It has applications in various industries such as energy and telecommunications. Although it started as a proprietary protocol for communicating with SCADA systems in the energy industry, it has evolved into the leading open-source protocol for connecting industrial Internet of Things (IoT) devices.

The publish/subscribe model of MQTT is designed to maximize the available bandwidth. This can be envisioned in the figure listed below. Instead of having a client-server architecture, it uses a decoupled model that enables the client to communicate with an endpoint. Instead of having to contact each other, the publishers, and subscribers of MQTT can only communicate with third parties through the protocol. When a device sends data to a server, it is called a publish. It is also called a subscribe when it wants to subscribe to specific topics. If the connection is disconnected, the broker can send a cached message to the subscriber. The messages are then passed to the subscribers. The publisher and subscriber are respectively referred to as clients and subscribers. They can be devices or applications that run an MQTT library. Figure 4.33 shows a typical MQTT communication diagram.

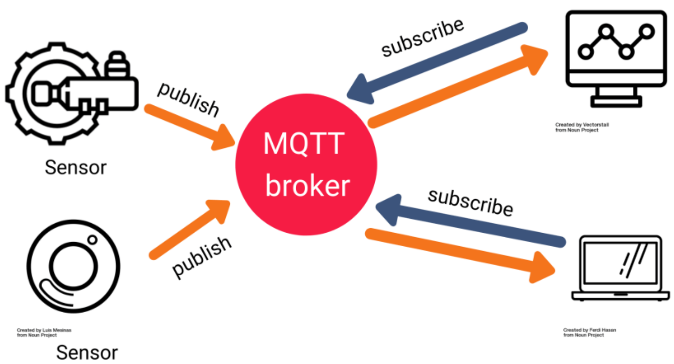

Figure 4.33: MQTT Communication Diagram

An MQTT broker acts as a go-between between the parties sending and receiving messages. It sends and receives messages before they are delivered to the subscribers. A broker that can handle millions of concurrent users is considered a good choice. The lightweight nature of the MQTT protocol and its minimum overhead help minimize the load on the server.

Among the advantages of MQTT are its low network usage, lightweight nature, and ability to distribute data efficiently. Its ability to provide fast message delivery also makes it a good choice for remote monitoring and control. Compared to other protocols, MQTT has a slower transmit cycle. Also, it uses a different resource discovery system. Instead of HTTP, it uses TLS/SSL for encryption. This is because the protocol was not designed to provide secure encryption. The complexity of MQTT's topic structure makes it hard to create a globally scalable network. As the size of its tree grows, the complexity of its network increases.

Due to the binary nature of the message payloads, it can be difficult to identify the exact encoding of the messages. Also, its lack of authentication features can create problems for different applications. Unfortunately, using MQTT requires the use of TLS, which is not a lightweight protocol. When authenticating clients, it is not possible to control who owns the topic or publish its contents. The lack of security features makes it easy to inject malicious messages into the network. Also, it prevents the message receiver from knowing who sent the original message.

Zigbee

Zigbee is an IEEE 802.15.4-based specification that enables low-power wireless communication protocols for home networking and other low-power applications. Zigbee is a wireless ad hoc network that enables low-power, near-peer networking. It is intended to be more cost-effective and simpler than other wireless networking technologies such as Wi-Fi. It is commonly used in home energy monitoring systems, wireless light switches, and other industrial equipment that require short-range wireless data transfer. Zigbee devices can easily transfer data over long distances by routing it through a mesh network of intermediate devices. Its low data rate of 250 kbits per second enables reliable and secure networking. Zigbee is a low-cost, energy-efficient mesh network standard that's ideal for monitoring and controlling battery-powered devices. It operates in the 2.4 GHz band and is commonly used in medical and industrial applications.

Data rates vary from 20 kbits per second to 250 kbits per second. Zigbee's physical layer and media access control are built into its platform. The other key components are network layer, application layer, and manufacturer defined ZDOs. ZDOs are responsible for various tasks, such as keeping track of device roles, setting up network rules, and enforcing security policies. The central component of a star network is the coordinator, which acts as the network's central point. It coordinates the various operations of the network.

4.3.9 Other Communication Protocols

VNC

Virtual Network Computing is a desktop-sharing system that enables one computer to remotely control another. It sends the keyboard and mouse input to the other computer, and it updates the graphical-screen updates over a network. Multiple clients can connect to a server at the same time using Virtual Network Client (VNC). This technology allows users to access files stored on their work computer from their home computer.

The original source code of Virtual Network Computing is available under the GNU General Public License. There are also a number of variants of the system that offer their own special features, such as file transfer or optimized for Microsoft Windows. Usually, a viewer connects to a server using a standard port. However, it can also connect to the server using a browser. In listening mode, a client can connect to a server without requiring the server to configure its firewall. This feature saves the client from having to set up its own firewall. It also allows a viewer with no technical background to connect to the server.

The basic concept of the VNC protocol is that it can use a lot of bandwidth to carry out its tasks. To reduce the communication overhead, various methods have been developed. The simplest way to transfer data is to use raw encoding, which sends data in a left-to-right scanline order. This method works well if the screen changes only a small portion of the time. However, it can get very heavy if the number of pixels changes at the same time. Usually, it uses the TCP port 5900+N. Some implementations start with a basic HTTP server and provide a Java applet to allow easy connection to any Java-capable browser. Even on low bandwidth, a viewer can still connect to the Internet.

Although it can be done remotely, establishing a connection may require the proper configuration of the network address translation (NAT) and the appropriate firewall settings. You can also use a remote network connection (VPN). Xvnc is a Unix server that displays client windows. It is typically referred to as an X server when used by remote users. However, applications can still appear on the server as if they were a normal X display. Alternatively, a machine with a keyboard, mouse, and screen can be set up to run the server as a service or a daemon. It can then remove the display and its components, such as the keyboard and mouse, from the machine.

On Linux and Unix systems that support multiple X11 sessions, the system can start a new X11 session or serve an existing one. On Microsoft Windows, the current user session is used. For Mac OS X, Apple Remote Desktop for Mac OS X works seamlessly with the Xvnc client. It can also connect to a user's current desktop if it's served with x11vnc or if it's served with TightVNC. Although RFB is a secure protocol, it doesn't encrypt passwords. A network can still break this feature by sniffing the encoded and the plain-text passwords.

For security reasons, it's recommended that the user's password be at least 8 characters. Some versions of the protocol also have an 8-character limit. In addition, some versions of the protocol support an encryption plugin that can prevent unauthorized access to the server. RealVNC supports authentication using Active Directory and NTLM accounts. However, using encryption plugins can prevent it from working seamlessly with other programs. According to the developers of TightVNC, the protocol is not secure as it sends data without encryption. To prevent this, the client should be tunneled through a secure SSH connection. There are a wide range of SSH clients available for various platforms. Some of these include UNIX, Windows, and Mac OS X. Aside from these, there are also freeware solutions that allow people to create encrypted tunnels between their devices.

SSH

The Secure Shell Protocol is a cryptographic network protocol that enables secure access to network services over an unsecured network. Its most commonly used applications are remote login and command-line execution. It is composed of three components: the transport layer, the user authentication protocol, and the connection protocol. Unix-like operating systems is served by the Secure Shell, which was first designed in 1995. It is a replacement for the Telnet and other insecure remote Unix shell protocols.

The initial development of the protocol was carried out in various developer groups. There are two major versions of the protocol: the first is known as SSH-1 and the second is known as SSH-2. Secure Shell is a cryptographic network protocol that enables the remote computer to authenticate its user. Basically, it works by automatically creating public-private key pairs to secure a network connection. The user then generates the public-private key pair manually. This method ensures that the authentication is performed. The public key is placed on the computer to allow the user to access the owner's private key. However, since the key is never transferred to the network, the user's authentication is never affected. In order to prevent unauthorized users from accessing your network, it is important to verify the public keys used by the system before accepting them as valid.

Remote users typically use the protocol to perform various tasks, such as accessing a remote machine and executing commands. It can also transfer files using the associated protocols. An SSH client is used to establish connections to an authorized server. Most modern operating systems, such as Mac, Linux, and Windows, support the use of both the standard and the advanced versions of the protocol. However, versions prior to Windows 10 do not support the use of the protocol.

For file managers that support UNIX-like operating systems, the FISH protocol can be used to provide a split-pane interface. The WinSCP client can also perform various file management tasks using PuTTY. Both the WinSCP and PuTTY are available as standalone programs that can be run directly off a USB drive. Setting up an SSH server in Windows is typically done through the Settings app. In Windows 10, an official port of OpenSSH is available. This feature allows users to connect to a cloud-based virtual machine without exposing it to the Internet.

An SSH tunnel can be used to connect to a virtual machine. The Internet Architecture Network (IANA) has designated various ports for this protocol, such as 22 and SCTP. These ports are commonly used by servers that support the protocol. The various versions of the protocol are used in various file transfer methods. Some of these include SCP, which is a more efficient alternative to FTP. SFTP is a secure alternative to FTP that can be used to transfer files over a network connection.

4.3.10 Programming Languages

In addition to modes of communication, programming languages is another crucial component of our design as we need a way to be able to interpret all the data that our hardware will be collecting. There are numerous programming languages available; however, some will be more beneficial than others to use in this application. C is a popular choice for embedded systems or any hardware-related applications, while Python is general in its applications. Each language has their benefits and downfalls, so we must make a reasonable decision in which programming language to use for our design.

C

C is a general-purpose programming language that supports various types of programming, including structured programming and recursive programming. It has been used in many applications that were previously written in assembly language. C is commonly used for developing operating systems and other applications for computer architectures that include embedded systems, supercomputing facilities, and programmable logic controllers. It was used during the development of the Unix operating system. During the 1980s, it gained widespread popularity. It is used by many different computer platforms and operating systems. ANSI C has been widely used since 1989. It was developed to provide a low-level programming language that is easily accessed and mapped to machine instructions. Despite its low-level capabilities, the C language was designed to encourage programming that is cross-platform. A C program that is built with minimal changes to its source code can be compiled for various platforms.

C is widely used for programming in embedded systems and operating systems. Its code can be written for portability, yet it can also be used to access and modify hardware addresses. It can also be used to implement website programming using the Common Gateway Interface. C is often chosen over interpreted languages due to its portability, ease of use, and near-universal availability. A consequence of this is that compilers and interpreters of other programming languages are commonly used in C.

Since some libraries and other programming tools can be written in C, it can be commonly used as an intermediate language. This approach is usually used for portability or convenience. Some of the features of C are still missing, which has prompted the development of other C-based languages that can be used as intermediate languages.

C++

C++ is a programming language that was created by Bjarne Stroustrup. It has evolved significantly over time and now includes object-oriented constructs and functional features. C++ is a programming language that is usually built as a compiled version. Numerous vendors support it, including IBM, Microsoft, and Intel. It is designed to work seamlessly across various platforms.

C++ has been widely used in various contexts, such as web search, e-commerce, and databases. It is also commonly used in infrastructure-focused applications, such as video games. It is also widely used in performance-critical applications. In 1998, the C++ programming language was standardized as part of the International Organization for Standardization's (ISO) 14882:1998 standard. It was initially developed by Stroustrup as an extension of the C language. Before its standardization, he wanted a more flexible and efficient language that could be used by developers.

C++ is the programming language that is used by most of the major operating systems. Being able to develop an operating system in C++ makes it very fast and easy to implement. C++ is a very close cousin of the assembly language. This makes it possible to write lower-level operating system modules. Due to its low-latency, low-complexity, and high-quality, many low-latency systems implement C++ as their programming language. For instance, many high-end libraries rely on C++ as their main programming language. Due to the complexity of the math involved in learning machine learning models, many libraries have had to provide high-performance computing. C++ is typically used to provide the necessary performance.

C++ is commonly used as the main programming language for software that handle various high-end processing tasks such as image processing, computer vision, and graphic processing. Even the popular video games industry is also known to use C++ as its main programming language. Due to the high number of transactions that banks process daily, C++ is the preferred choice for banking applications. It is also used in distributed systems due to its ease of use and connection to the hardware. In cloud storage systems, C++ is often used as the programming language of choice since it is very close to the hardware and provides high-complexity and load tolerance. This is also due to its multithreading libraries.

Database software is commonly used in various applications that we use every day. Due to its proximity to the hardware, C++ is commonly used as the main programming language for embedded systems such as medical devices and smart watches. Due to the presence of lower-level languages, C++ is more advantageous than other programming languages when it comes to compilation systems.

Python

Python is a programming language that emphasizes code readability and object-oriented design. Its various constructs and object-oriented approach help developers create clear, logical code. It supports various programming paradigms, such as structured programming and object-oriented programming. It is often referred to as a "batteries included" language. Python 2.0 was released in 2000, and it included new features such as list comprehensions and Unicode support. In 2008, Python 3.0 was released, which is not backward compatible with older versions.

Python is a multi-platform programming language that supports both object-oriented and functional programming. It also supports several other programming paradigms, including design by contract and logical programming. Python supports various programming traditions, such as Lisp. Its dynamic name resolution provides a binding between methods and variable names. The standard library has two modules: functools and itertools. Both of which are based on the same functional tools. Its core philosophy is based on aphorisms, which can be found in the document "The Zen of Python". The compact modularity of Python has made it popular to add programmable interfaces to existing apps. Unlike Perl, Python has a "there should be one" philosophy. According to Alex Martelli, a Fellow at the Python Software Foundation, Python's developers do not consider anything as "clever" as it is not considered a compliment in the culture. When time is of the essence, a Python programmer can move time-sensitive functions to extensions that are written in C or Python.

MicroPython

The MicroPython operating system is a low-level Python programming language that can run on most standard microcontrollers. It is optimized to work in constrained environments. MicroPython is a Python-based programming language that features many advanced features, such as an interactive prompt, list comprehension, and generators. It is also compact enough to run in just 256k of code space.

MicroPython is a full-fledged Python compiler and runtime that works on the bare metal. It features an interactive prompt, which can execute commands immediately. It also has built-in utilities that allow you to run and import scripts. Aside from implementing core Python libraries, MicroPython also includes various modules that allow developers to interact with low-level hardware.

4.3.11 Operating Systems

To collect data in an orderly fashion on our Raspberry Pi, we will need a lightweight, efficient operating system. There are many choices available on the open-source market, but we will be looking at two different options for our application: Linux Ubuntu and Linux CentOS.

Linux CentOS

The CentOS Linux distribution is a repository built on the Red Hat Enterprise Linux platform. Its stable, predictable, and reproducible nature make it a great choice for anyone who enjoys distributing Linux. Today, we started the process of delivering a transparent governance model, which includes increased transparency and access. This will be followed by a release of our own roadmap.

CentOS Linux is a free and open-source operating system that aims to be compatible with Red Hat Enterprise Linux (RHEL). It is developed by a small team of developers and is supported by a robust community. The CentOS Project is a semi-autonomous entity that draws on the Apache Foundation's structure. Its governing board is composed of various special interest groups.

Linux Ubuntu

Ubuntu is a Linux distribution that's made up of mostly open-source software. It's usually used for desktop computers and can run on various Internet-connected devices. Ubuntu is a widely used operating system for cloud computing. It has a default desktop named GNOME, and it supports various cloud computing platforms, such as OpenStack. Its long-term support is available until 2030.

The latest version of Ubuntu is called 21.10 and is supported for nine months. It is distributed by Canonical, a British company that specializes in distributing open-source software. It is owned by a group of developers known as Canonical, which generates revenue by selling premium services related to the operating system.

4.3.12 DATA STORAGE METHOD

Once we've successfully delivered our data to our Raspberry Pi, we need to store said data in an organized database to allow for easy access and interpretation. Once our data is stored in a database, data analysis and manipulation can occur to make sense of our collected data. There are many types of databases and technologies we can implement, such as SQL and its various flavors, MongoDB, and many more. We will discuss some of these options in this section.

SQL

SQL is a domain-specific language used for programming and managing data in databases. It is commonly used to handle structured data, such as data with relationships among entities and variables. There are several advantages of using SQL over older read-write APIs. SQL was introduced to simplify the process of accessing many records with one command. It eliminates the need to specify the method to access a record. It consists of various statements that are commonly abbreviated as sublanguages.

The scope of SQL is broad: it can query data, perform various data manipulation techniques, and provide data access control. Although it is mainly used for programming, it also includes procedural elements. The model that was described in Robert Codd's 1970 paper was first described in a study that focused on the relational model of data. Despite not entirely following the model, it became the most popular database language. Since the inception of the standard, it has been updated to include many new features. Despite the existence of the standards, most of its code still requires some changes before it can be ported to other systems.

MySQL

MySQL is a type of open-source database management system. It enables users to create, modify, and publish databases that are designed to work seamlessly with each other. SQL is a programming language that enables developers to create, modify, and extract data from a relational database. It also controls the user's access to the database. Aside from databases, MySQL also supports various other features, such as network access and backup. MySQL was originally created by MySQL AB, a Swedish company that was acquired by Sun Microsystems in 2010. After Oracle bought Sun, Widenius forked the open-source project and created MariaDB. MySQL is a component of the LAMP stack, which is an acronym for Linux, Apache, PHP, and Python. It is commonly used by web developers to create and manage database-driven applications.

There are also free and third-party administration applications that integrate with MySQL. They allow users to easily work with the database's structure and data. MySQL Workbench is an integrated environment that allows users to create graphical representations of the MySQL database's structures. It is available in three editions: the free and open-source Community Edition, as well as the Standard Edition.

MySQL also ships with many command-line tools, such as the MySQL client. These utilities are designed to perform common tasks and administrative tasks. Percona Toolkit is a utility that can be used to test the reliability of a MySQL database, fix corrupt data, and speed up servers. It is included with various Linux distributions.

NoSQL

A NoSQL database is built for specific data models and can be used for building modern apps. It's widely recognized for its ease of development and performance. With its flexible nature, NoSQL databases are ideal for modern apps that require high-performance and flexible databases. NoSQL databases can handle various types of structured and unstructured data. Unlike traditional databases, NoSQL databases can scale out by accessing distributed hardware. Some cloud providers provide end-to-end managed services that allow their customers to run smoothly.

There are many ways to store data in NoSQL database. Some examples include key-value store, document store, and graph. The key–value store model is a non-trivial data model that stores data in associative arrays. This model represents data as a collection of key pairs, which appear at most once in the collection. An extension that maintains key pairs in lexicographic order is known as the key–value model. This feature can retrieve selective key ranges. Some databases support the ordering of keys. In most cases, they can store data in memory or on solid-state drives. A document store is a type of database that stores data in a variety of formats and encodings. Most commonly, these include text formats like YAML, XML, and binary forms like BSON. A document-oriented database sends a unique key to the database to represent the contents of a specific document. An API or query language can then retrieve the documents based on their contents. Although table and collection records have the same sequence of fields, they have different fields. A graph database is a type of database that draws on the relationships between various elements. It can store data such as public transport links and social relations.

MongoDB

MongoDB is a leading open-source NoSQL database. MongoDB is a document-oriented database that provides high-performance, easy-to-use, and flexible management. It works seamlessly across various platforms. A single MongoDB server can have multiple databases. A collection is a group of documents that can be stored within a single database. It doesn't enforce a specific type of schema and can have different fields depending on its purpose. MongoDB documents have dynamic schema. This means that instead of having the same set of fields and structure, they can have different types of data. MongoDB has official drivers for various programming languages. There are also unofficial drivers for other frameworks and languages. It has also introduced a native GUI for managing and viewing data.

4.3.13 PCB Enclosure

Enclosure

Our final circuits need to be boxed safely when it is going to be installed outdoors. Talking outdoors installation, many things can happen regarding the safety and the security of the components such as harsh weather, very high temperatures, rain, severe storms, and exposure to dust and dirt. All those conditions can impact and contribute to a short lifetime, a malfunction, and a destruction of the device. To prevent such of events, we need to use an enclosure that can protect the device under certain standard requirements conditions. To choose the appropriate enclosure for our design, we need to consider those factors: protection rating, certification approvals, size, access needs, cost, temperature environment, and corrosion resistance.

Protection Rating and Certification Approvals

To make sure about the type of enclosure to use, the enclosure protection rating is important to ensure the degree of the protection that will be provided for the inside equipment. In other terms, rating the enclosure protection means that what is the level of protection that enclosure can provide to secure the equipment from dust, dirt, liquids, and more. Usually NEMA (National Electrical Manufacturers Association) rates that type of level protection of enclosure. An electronic enclosure that is falling on NEMA 4X has a high degree of protection. Below in an example of Enclosure protection rating.

Size

The size is the dimension of the enclosure where the equipment will be installed. The size varies with the size of the component meaning that the height, the width, and the depth of that component is and by that we can choose the proper or approximate enclosure for our device. In our case the size of the PCB is approximately 3”X3” and the height of the component remaining pending until the final touch.

Access needs

The accessibility to the components inside the enclosure usually makes with a front door or a cover. That door or cover can be locked with quarter turns, latches, clamps, handles, or screws. Regarding to the type of security that we are looking for we can make the proper choice. When security does really matter, other optional accessories can be added such as padlock hasps, tamper proof screws, or key lockable hardware.

Cost

Cost is also another important aspect when choosing enclosure protection. Normally, price and quality always come to a challenge in people choices. As the quality of a product is high the cost of this product goes up and it is true for the reverse phenomenon when the quality of the product is low the of this product is low also. That means, when making our choice for the appropriate enclosure both aspects of quality and price should take into consideration base the customer requirements.

Temperature

Another crucial factor when it comes to enclosure protection is temperature. Temperature is important key for the device inside the enclosure. The ambient temperature either high or low can negatively affect the efficiency of the device when it is boxed in the environment. However, as we are living in a tropical state where the ambient temperature in Florida is most of the time high. For this reason, we need to investigate the ambient temperature and the device temperature tolerances in order to find the right enclosure protection. In this case compared to the size of the component a larger enclosure might encounter this issue. In addition, there are other options that we can consider compensating the heat from the ambient and the heat dissipated by the components such as using cooling fans, or heat sink devices.

Corrosion Resistance

Depending on the type of materials using for enclosure, the environment can affect enclosures and makes them very corrosive. Manufacturers for enclosures use special materials like stainless steel, aluminum, polycarbonate, and fiberglass to encounter these environment issues. A type NEMA 4X standard rated is an example of enclosure protection rating for corrosion resistance.

Figure 4.34 display two candidates for a PCB enclosure for the All-In-One PV Sensor.

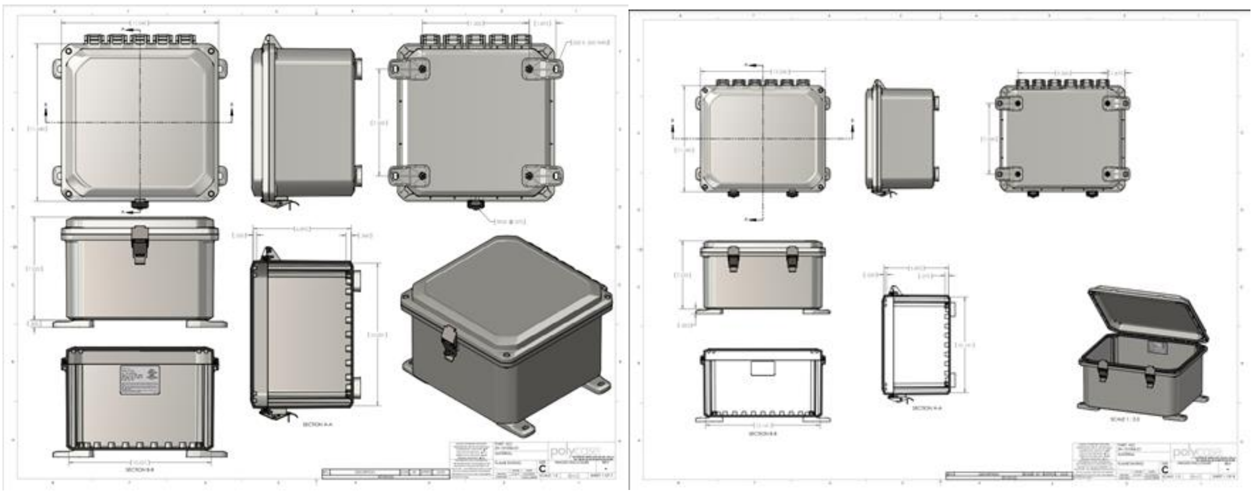

Figure 4.34. Layout of theZH-101006 and ZH-121006 Hinged NEMA enclosures, respectively

We have searched for enclosure protection for our design, and we have found a couple of options that might be an excellent choice for our components. From Polycase, we saw the ZH-101006 and the ZH-121006 Hinged NEMA enclosure. They were made with impact-resistant polycarbonate materials especially to be installed outdoors with standard requirements protection against weather, water, corrosion, dirt, and dust hazardous. These enclosures have been rated by NEMA UL and other associations for diverse levels of protection. The rated for those enclosures are IP65, IP66, IP68, NEMA 3S, 4, 4X, 12, and 13 rated. The difference between those two types of enclosures is resided in extra features so one can have and the other one does not have and cost also. Table 4.16 below summarizes the difference between the two enclosures.

Table 4.16: Comparison of the ZH101006 and ZH121006 NEMA Enclosures

Enclosure	Rating	Size	Cost ($/Unit)	Extra Features
ZH-101006	IP66 NEMA 3S, 4X, 13	11.04X11.04X7.52in	54.41	Single Padlock
ZH-121006	IP66 NEMA 3S, 4X, 13	13.24X11.24X7.70in	56.04	Double Padlock

5. SYSTEM DESIGN

To move forward with the creation and testing of the All-In-One PV Sensor, the prototype must have a completed schematic and corresponding EAGLE design. In this section, the EAGLE design for the AIO PV Sensor will be discussed. This design will eventually be used to create the PCB layout of the board as the components can be selected and their respective footprint on a board can be compared to one another and assembled on a board.

The EAGLE design will feature every component of the All-In-One PV Sensor including the pyranometer and thermocouple as their existence on the board must be accommodated whether they are connected to it.

5.1 HARDWARE DESIGN

The hardware design for the All-In-One PV sensor will fully encompass the components that will be present on the PCB attached directly to the Solar Array's outputs. Therefore, all hardware for this includes the Voltage and Current Sensors, the Thermocouple, the Pyranometer, the On-Board Power Supply, and the MCU.

5.2 TERMINAL CONNECTIONS

In order to measure signals, we must first connect them to the PCB. This is done via Terminal Blocks with differing gauges depending on the source of the signal. For the Panel's voltage input which will be used to measure voltage and current, a 10 Gauge AWG terminal block will be used. For the smaller order inputs from the pyranometer and thermocouple, a 16 Gauge AWG terminal block will be used instead.

The panel's input can be seen in Figure 5.1.

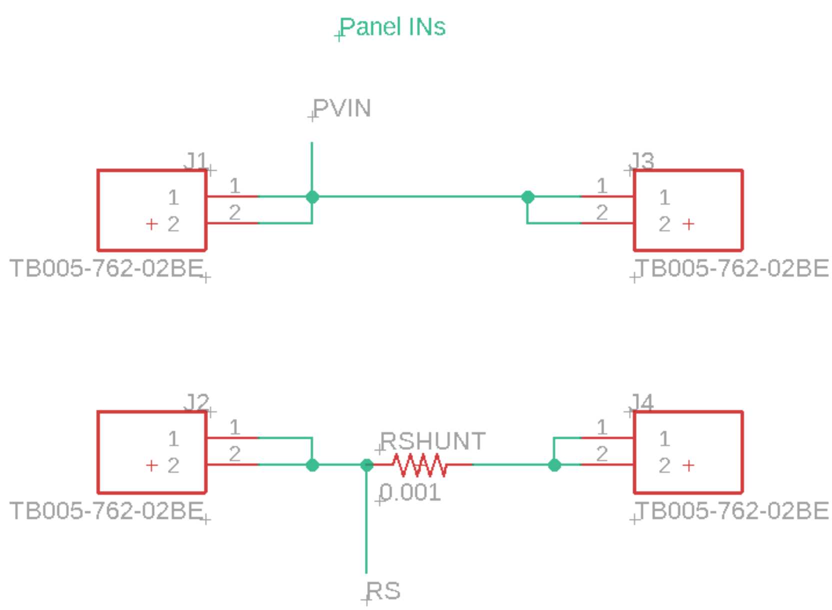

Figure 5.1. Panel IN and OUT

On the left-hand side, the voltage and current generated by the solar panel come into the PCB through TB005-762 Series Terminal Blocks, capable of holding 10 AWG wires to withstand the large output of the solar panel. Because we want our design to have minimal impact on the voltage and current generation of the panel, the inputs are passed directly through to the outputs via a new set of TB005-762 Series Terminal Blocks.

Along the way, the positive side of the solar panel's output is taken as PVIN and a value measured across a shunt resistor, RS, is taken as well. This shunt resistor serves as a current measuring component using Ohm's law to correlate the voltage drop across the small resistance to its total current by dividing the voltage by its resistance. This decision was inspired by the TIDA-00640 which proved that, given a module can produce a maximum of 300 Watts, the panel would only lose a maximum of 0.03% power from the existence of the shunt:

$$\%\text{ power loss from shunt} = \frac{\text{Shunt power dissipation}}{\text{Maximum module power}} \times 100 = \frac{0.100\text{ W}}{300\text{ W}} \times 100 = 0.03\%$$

Along with the Solar Panel's voltage and current being taken into the PCB, the pyranometer and thermocouple outputs are taken in. The model used for the terminal blocks in Figure 5.2 are the 1727010 PCB terminal Blocks.

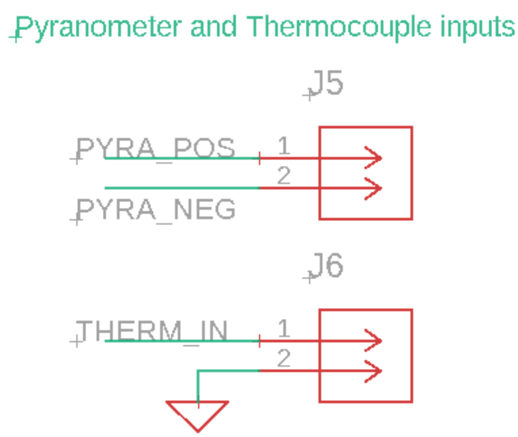

Figure 5.2. Pyranometer and Thermocouple inputs

These inputs are relatively simple as the components that are used to amplify or deliver these signals to the ADC will be placed directly on the PCB, independent of the pyranometer or thermocouple's existence in the application. Both the pyranometer and thermocouple are expected to have relatively small outputs in terms of voltage, so they must be amplified. This will be expanded upon in sections 5.5 and 5.6.

5.3 On-Board Power Supply

All on-board components are powered through the VCC of the board which was decided to be 3.3V to satisfy various turn-on voltages for the different components across the PCB. This VCC is created by the LM5017 Step-Down Regulator, capable of taking 100 V and stepping it down to an acceptable 3.3 V level. This can be seen implemented in our EAGLE design in Figure 5.3.

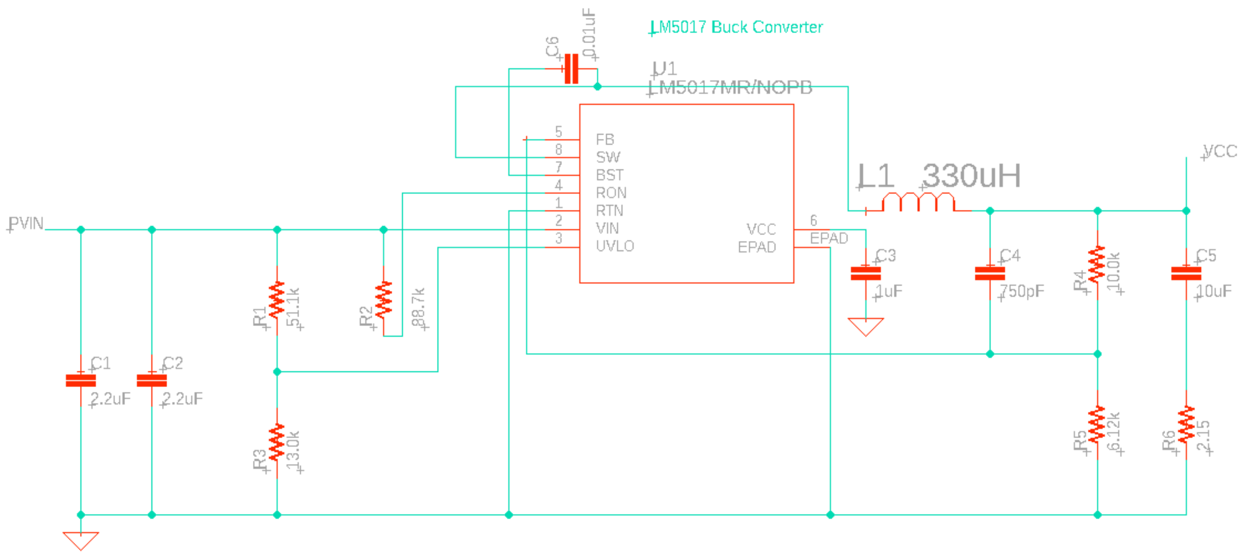

Figure 5.3. The LM5017 Step-Down Regulator

The LM5017 was selected due to its small current draw requirement and its ability to regulate relatively high voltages compared to what we expect from the Solar Panels that the All-In-One PV Sensor will be installed on. To minimize costs, the Type 2 LM5017 is selected. The respective type of the LM5017 is determined by its Ripple Configuration, and the Type 2 configuration can be seen in Figure 5.4.

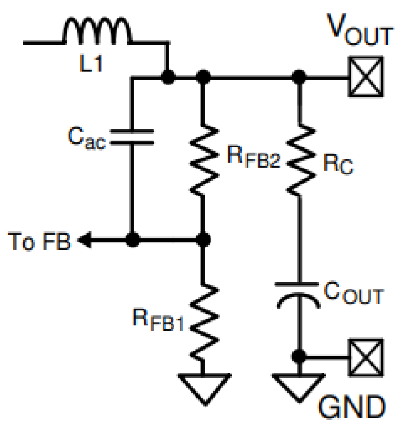

Figure 5.4: The Type 2 LM5017 Ripple Configuration

This implementation can be seen on the righthand side of the LM5017's implementation in EAGLE. This selected variant has a less stable VCC, but a stable VCC will not be required as the components in our PCB do not need a constant 3.3V to operate, so long as it falls within a reasonable range.

Despite its implementation, the specific need of an LM5017 is not necessary - this step-down regulator can be replaced by any other regulator so long that it can receive an input of 40 V and outputting a controlled voltage of 3.3 V.

5.4 Current and Voltage Sensing

The next section of our EAGLE design lies in the current and voltage sensing circuits. The shunt resistance is used to measure a small voltage across a shunt resistor, but that must be sent to an Op-Amp to be compared to ground and sent to an ADC to prevent the loading effect. Similarly, the voltage must be sensed using the input of the solar panel and sent through an Op-Amp so that it can be converted. This configuration can be seen in Figure 5.5.

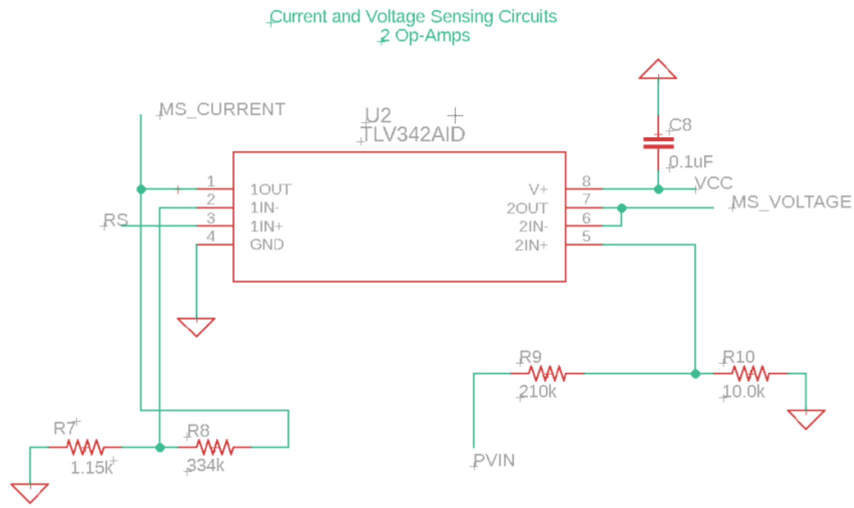

Figure 5.5: Current and Voltage Sensing Circuitry, TLV342 Op-Amp

The selected Op-Amp for our EAGLE design was the TLV342, chosen as it was for the TIDA-00640 reference design. This Op-Amp has a low offset and is specifically designed for low voltage operation which is ideal for our implementation. The VCC is sent into this Op-Amp and is coupled to minimize noise injection and both Op-Amps in this dual module are utilized for current and voltage sensing.

The current sensing circuitry is on the left-hand side of the TLV342. The measured voltage across the shunt resistor is sent into the positive input of the Op-Amp, and the negative input is compared to ground across a 1.15k resistor and sent as a measured current, MS_CURRENT, over a 334k resistor to the ESP32's ADC to be converted. The 334k resistor serves to amplify the measured voltage so that the ADC can easily translate the received signal into tangible, digital values. The voltage that is measured across the shunt resistor is in the millivolt range, and the amplifying circuit brings it up to no greater than 3V.

A voltage divider is implemented on the right-hand side to simply measure the current. A voltage divider was chosen as the method of measuring the Panel's voltage output due to its simplicity and therefore its low cost. Because we want to measure the panel's direct output voltage, the value PVIN is sent over a voltage divider of 210k ohms and compared to ground over a 10k resistor. This large voltage divider is able to bring an input of 35V down to 688mV before being sent to an ADC making it incredibly efficient and safe for the ADC's input. The measured voltage across the voltage divider is sent toward the ESP32's ADC as MS_VOLTAGE.

5.5 Temperature Sensing

As noted in Section 5.2, the expected output of the selected Thermocouple will likely be in the millivolt range. Along with this, thermocouples need reference nodes to compare their measured temperatures to to maintain a higher degree of accuracy. For this reason, the MAX6675ISA is selected as the Thermocouples integration to the board, seen in Figure 5.6.

Figure 5.6. The MAX6675ISA used to connect the thermocouple to the AIO-PV Sensor

The MAX6675ISA features internal amplification and reference (cold) junctions for the thermocouple to function: It must reference the temperature that it measures to a constant temperature, the cold junction, and those small voltages that are read from the comparison of the two junctions must be amplified so that the ADC can translate them into digital values. The MAX6675ISA takes the thermocouple's input, THERM_IN, and uses it internally to send outward to the ESP32 via THERM_SO, THERM_CS, and THERM_SCK.

5.6 IRRADIANCE SENSING

Just as the thermocouple has an on-board amplifier for its relatively small signal, the pyranometer is making use of the INA126PA Instrumentation Amplifier to amplify its small maximum signal of 200mV to a new maximum of 1V, allowing the on-board ADC of the ESP32 to easily read the signal output by the pyranometer. The INA126PA can be seen in Figure 5.7.

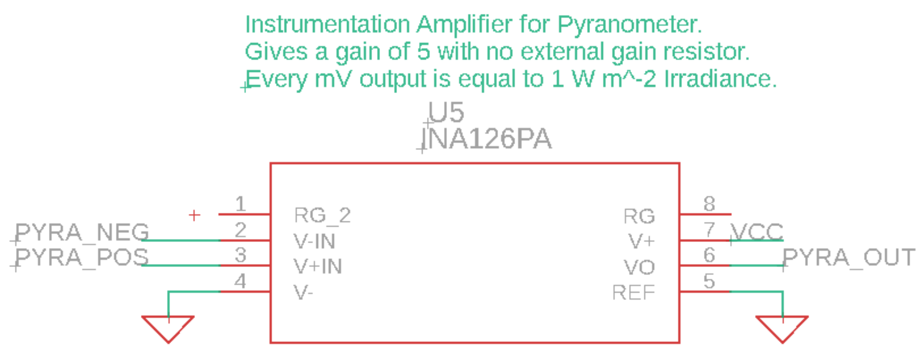

Figure 5.7. The INA126PA for Pyranometer Amplification

The INA126PA can take the pyranometer's dual output and give it a baseline gain of 5 such that the lowest possible output is now 1 mV. This instrumentation amplifier was deemed necessary after discovering that the on-board ADC of the ESP32 had a resolution of 0.8mV while the SP-110-SS output 0.2mV per 1Wm^-2, meaning that we would only be able to detect a change with every 4 Wm^-2 of sunlight irradiance.

6. COMPONENT TESTING

In this section, the testing of the All-In-One PV Sensor and its individual components will be explained. While we do not currently possess all of the materials necessary to truly test, the plans and methods to test those components still exist and will be explained. For the software side of the All-In-One PV sensor, we will conduct several tests that will show how the ESP32 is able to create its own local access point and how the data from the sensors will be translated and transferred into a database.

6.1 HARDWARE TESTS

In section 6.1, the methodology behind the testing of our individual components will be discussed. When the physical components are available to us, this section will also feature the results of those tests and what the results mean moving forward.

6.1.1 ON-BOARD COMPONENT POWER SUPPLY TESTING

Since we don't have all parts yet, we cannot do a physical testing for the power supply. However, according to our schematic a power supply can be processed as follows. The testing of the power supply is processed by having input voltage of various range from the input terminal and check the results with a multimeter to see the expected outpout voltage on the output terminal. Thereon, we can discuss the results and come with futher analysis

6.1.2 VOLTAGE & CURRENT SENSOR TESTING

Before designing and implementing the real circuit for the voltage and current sensing, we first must test the accuracy of the TLV342A to ensure that we can achieve the desired outcome. To verify the functionality of the op amp, the TLV342A would be tested with a DC voltage generator and multimeter, this will prove the result that we are trying to achieve; 1.77 V for the current sensing, and 2.3-2.5 for the voltage sensing. The sensing would also be tested with the ESP32-Wroom-32; this would allow us to view the values produced by the ADC. The way we would perform these tests is by mounting The TLV342A on a through hole PCB, adding necessary electronic components on the board. The TLV342A uses SMD technology, so it must be soldered onto the PCB using header pins. The resistors we plan on using will also be soldered onto the PCB, then a DC power generator will energize the amplifier. 0.00891 V will be supplied to the current sensing side of the amplifier (pin 3), since the maximum voltage across the shunt is expected to be 0.00891 V. The output voltage will then be measured; after the amplification, a voltage range of 2.3 – 2.5 V should be seen.

For the voltage sensing, 39 V would be sent to the input of the op amp (pin 5) since the maximum voltage output from the solar panel is 39 V. The voltage moves across the voltage divider, then 1.77 V would be sent through the unity gain buffer. The output voltage would be measured by the multimeter expecting a value of 1.77 V. After this test is done, with the hope of success, we would then attach the ESP32 chip to the circuitry. The voltage and current sensing outputs would be attached to the ADC pins of the ESP32; the chip would be programmed to enable the use of the ADC ports, then the amplifier would send the results to the ESP32. The results would be transmitted wirelessly to a receiver which would display the values coming out of the sensor.

Later, the PCB would be connected to a solar panel producing a voltage in the range, but at this time the buck converter would be attached, stepping down the voltage applied to the amplifier. The current and voltage sensing part of the amplifier would then be attached to the input of the solar panel, then the values would be measured.

6.1.3 Temperature Sensor Testing

To test the voltage sensing abilities of the MAX 6675 for our first preliminary testing, we used an of the shelve PCB that already has the MAX 6675 integrated chip and the capacitor already solder to do the primary testing. The primary testing that needs to be completed before proceeding with the reference design of using the MAX 6675 is to measure the overall resolution/accuracy of the system. To accomplish this, we attach a thermocouple temperature probe from a multimeter and the MAX 6675 with the same probe lead and compare the results and graphing them on chart then do the percent difference of all the possible temperature points.

The second phase of testing will be to analyze the same accuracy as we did before but this time with the given thermocouple and calculate the difference, we see between the multimeter thermocouple that is calibrated vs the uncalibrated Thermocouple provided by OUC. Figure 6.1 displays the connection names.

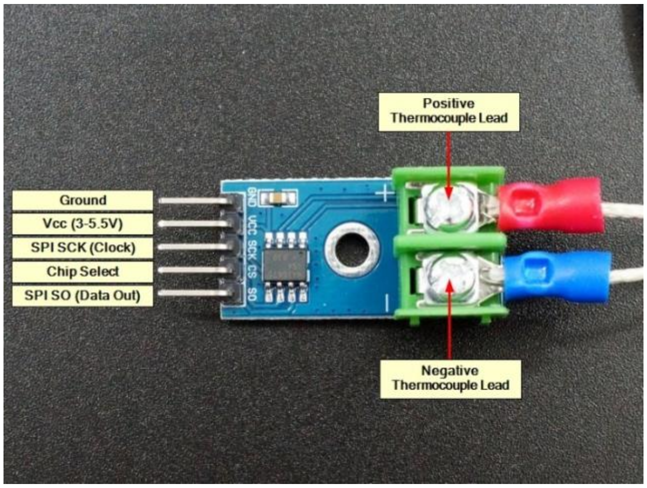

Figure 6.1. 6 MAX6675 thermocouple amplifier and compensator.

6.1.4 Irradiance Sensor Testing

To ensure that the pyranometer accurately reads irradiance and transmits it correctly to the on-board ADC, the pyranometer must be adequately tested. In most cases for electrical circuits, testing whether or not a part functions as intended is easy; datasheets exist for specific components, oscilloscopes and function generators can serve as catalysts to measure and control a specific parts performance, and so on. It is within this regard that pyranometers are inherently different. While a datasheet exists for this pyranometer, measuring the sun's irradiance cannot be done as easily through typical lab tools as measuring a voltage or current across a resistor, and the results are hard to verify on human intuition.

To test the functionality of the SP-110-SS pyranometer, an entirely separate pyranometer will have to be used such that the data from both pyranometers can be compared. For testing purposes, the separate pyranometer is actually a datalogger, a device that measures, records, and displays irradiance in a single controlled piece of equipment. This standalone device will allow us to measure irradiance with minimal noise or interference.

The datalogger that was used for testing the performance of the SP-110-SS is the Campbell Scientific CR300, provided by Rubin York of OUC. This datalogger was provided to the team alongside about 1 year of historical data from 2021 which provides us with another frame of reference for the theoretical output of the pyranometer.

Testing the pyranometer is now simple: The SP-110-SS must be connected to a device that can measure its output, that output must be converted into Watts per Square Meter, and the final result will be compared to the measured result from the datalogger and the historical data from the same day and time of the previous year. For the pyranometer's output to be measured and converted, one of two things must happen. The first option involves connecting the pyranometer to a breadboard which can further connect to an oscilloscope to measure its output in millivolts, and those millivolts can be multiplied by 5 to receive the irradiance in Watts per Square Meter. The second option is testing directly on the PCB; because the connection to the ADC on the board is entirely optional for the functionality of the All-In-One PV Sensor, the pyranometer can be plugged into the board via a terminal block and fed straight to the ADC, amplified by any implemented means. The ADC will then read the output of the pyranometer and send it to the local node to be displayed.

Of these two options, the former is preferred for two main reasons. Designing the PCB without the knowledge of how the pyranometer performs with and without an amplifier is foolish. It's entirely possible that the ADC's resolution is high enough to completely measure the pyranometer's millivolt signal without any means of amplification. Not only will testing the pyranometer on the breadboard save development costs for the PCB, but it will also give the team the freedom to experiment with what the pyranometer can use before it gets to a quantifying element such as an ADC or oscilloscope.

The pyranometer will first be tested on its own. If the pyranometer cannot give accurate results based on its specifications provided by Apogee Instruments, then it cannot be expected that the pyranometer will give correct readings when passed through an Operational Amplifier. For this reason, a simple Digital Multimeter will be used in accordance with the pyranometer when exposed to direct sunlight. Table 6.1 details the SP-110-SS's relevant functionalities.

Table 6.1: The SP-110-SS's Testing Specifications [4.20]

SP-110-SS	Value
Power Supply	Self-Powered
Current Draw	0 A
Output (Sensitivity)	0.2 mV per W m^{-2}
Response Time	Less than 1 ms
Field of View	180 degrees

When tested alone, the pyranometer gives accurate results. The SP-110-SS was tested in clear-sky conditions, and the pyranometer showed to be incredibly sensitive to its exposure to light down to the angle that it was pointed toward the sun's location in the sky. When pointed flat with the earth's surface while the sun was about 50% toward noon, the pyranometer saw an output of around 150 mV.

When pointed directly at the sun, the voltage output changed drastically to 204 mV, showing that the pyranometer is not only incredibly precise but incredibly sensitive. This must be considered in installation, as if the pyranometer is not exactly in line with the solar panel's angle toward the sky, it is likely that we will receive a different irradiance measurement than the panel is receiving.

6.2 Software Tests

While developing our prototype, we will constantly be conducting tests to ensure the reliability of our software. For example, we will be able to feed our software data values and ensure that data is properly delivered to our database and displayed on a GUI when necessary.

6.2.1 Wireless Communication Tests

To ensure sound wireless communication, we have thoroughly tested the Wi-Fi communication modules on board our ESP32 devices and Raspberry Pi and can clearly see that they are communicating reliably through Wi-Fi. During our first prototyping stages, we were able to confirm that our Raspberry Pi and ESP32 devices were properly communicating by being able to send temperature data from the ESP32 to the Raspberry Pi, being supported by the ESP32's broadcasted Wi-Fi access point.

7. ADMINISTRATIVE DETAILS

The fallowing sections below include the initial project description as well as the initial and overall project milestones need to successfully complete the "All-in-One PV Sensor".

7.1 INITIAL PROJECT DESCRIPTION & GOALS

The "All-in-One PV Sensor" consisted of fixing and redesigning some aspects of the previous design such as increasing the size of solar panel input of our sensor to accommodate 10-gauge wire. Designing a cheaper weather resistance waterproof casing for the sensor. In addition to the redesign of the thermocouple circuit design since in Phase I it did not work.

The initial phase of the project as in detail in Table 7.1 was to first recognize all the elements require by OUC, in addition to analyze previous attempts of the project such as Phase I. As we move on in getting familiarized with the "All-in-One PV Sensor". We came to the realization that Phase I design had critical flaws that required us to complete it redesign the previous design as it will not work properly as it was expected.

As seen on Table 7.1, 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.

Table 7.1: Initial Project Description and Goals

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	4/1/2022	In-Progress

7.2 PROJECT MILESTONES

In Table 7.2, we can see the introductory part of the projects where we assign specific dates to become familiarized with the team and the project itself. 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. This table details our in-class deadlines along with our research and development deadlines such that we keep on s healthy pace to complete our project by the end of Summer.

The final part of Table 7.2 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 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.

Table 7.2: Senior Design I Milestones

Number	Milestone	Tasked	Start Date	End Date	Status
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	In-Progress
8	First Draft Senior Design I	Group 6	2/14/2022	3/25/2022	Pending
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	In-Progress
12	Node/MCU and Communication	Andrew	1/28/2022	2/18/2022	In-Progress
13	Node/MCU and Pyranometer	Maguire	1/28/2022	2/18/2022	In-Progress
14	Power and Hall-Effect Sensor	Timothy	1/28/2022	2/18/2022	In-Progress
15	Power and Voltage Sensor	Valery	1/28/2022	2/18/2022	In-Progress
16	Filtering Circuit and Amplification	Group 6	2/4/2022	2/18/2022	In-Progress
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

On Table 7.3 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.

Table 7.3 is heavily forecasted for our progress in Senior Design 1.

Table 7.3: 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

7.3 PROJECT BUDGET

As on both Table 7.4 and Table 7.5 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 7.4 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 7.4: Initial Project Budget for Re-designing 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	TBD	$30	3	$30
6	Weatherproof Enclosure	Weatherproof cases	$100	1	$100
Total Estimated Cost:					$698.80

In Table 7.5 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 7.5 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.

Table 7.5: Phase II Budget

	Part Number	Component Description	Vendor	Unit Price	Quantity	Total Price	Notes
Wireless Transmission and Data Storage							
1	Not required as per MAE for Amazon	ESP-32S Development Board 2.4GHz Dual-Mode Wi-Fi	Amazon	$10.99	6	$65.94	In-stock
2	Not required as per MAE for Amazon	Raspberry Pi 4 Model B 2019 Quad Core 64 Bit WiFi Bluetooth (4GB)	Amazon	$134.99	1	$134.99	In-stock
3	Not required as per MAE for Amazon	SAMSUNG 128GB EVO Plus Class 10 Micro SDXC	Amazon	$19.10	1	$19.10	In-stock
4	Not required as per MAE for Amazon	HDMI Micro and Mini	Amazon	$6	2	$12	In-Stock
Sensors							
5	N/A	SP-110-SS: Self-Powered Pyranometer	Apogee Instruments	$223.00	1	$223.00	We might need to change it
6	700-MAX6675ISA	Thermocouple Amplifier	Mouser	$11.34	4	$45.36	It be cheaper buying the assemble one
7	TBD	Thermocouple Probes with Lead Wire & Molded Transition	Omega	$30.42	1	$30.42	N/A
8	TBD	Current Sensor	TBD	$4	4	$16	N/A

10	TBD	Voltage Sensor	To be determined	$3	4	$12	N/A
Power supply for 'All in One Sensor'							
11	TBD	MPPT Charge Controller	TBD	$23.99	4	$23.99	Board Power Consideration
12	926-LM5006MM/NOPB	LM5006 Series Switching Voltage Regulators	Mouser	X10 $4.11	10	$41.10	Best Option Yet
13	TBD	Connectors	To be determined	$20	2	$40	N/A
Testing Equipment							
14	Not required as per MAE for Amazon	Solderless Bread Board Kit	Amazon	$12.49	2	$24.98	N/A
15	TBD	PCB Development	TBD	$300	1	$300	N/A
16	Not required as per MAE for Amazon	uxcell Mounted Devices IC PCB Adapter Socket	Amazon	$8.08	1	$8.08	N/A
Total Estimated Cost + Estimated Shipping (+200$):							$1196.96

8. PROJECT SUMMARY & CONCLUSION

The goal of our project was to develop a low-cost, all-in-one photovoltaic (PV) sensor device which allows our customer, OUC, to gather data from their solar panel arrays. The all-in-one sensor collects voltage, current, temperature, and irradiance directly from the customer's solar panels. The data that our solution provides the customer with includes numerous benefits. Firstly, through voltage and current values collected at each panel in an array allows for technicians to detect a faulty panel in an easy-to-use manner. This solution significantly reduces loss of power generation when a panel becomes faulty as this reduces the time [and money] it would take for a technician to identify a faulty panel. Secondly, our solution collects 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 functions as a series of collector nodes, or microcontrollers, mounted onto each solar panel in an array. The collector nodes collect and wirelessly transmit multiple, granular pieces of data like voltage and current, temperature, and irradiance data from the onboard DC optimizers, thermocouples, and pyrometers, respectively, to a receiver node. The receiver node can 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 a much larger solar panel array.

Appendix A. References

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