OUC's All-In-One Photovoltaic Sensor Phase II

Group 6

Sponsored by The Orlando Utilities Commission, OUC

GROUP 6

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MOTIVATION

Solar Power is becoming more appealing

- Provides clean, renewable energy
- Reduces reliance on traditional fuels
- Installed and managed on-site

To ensure Solar Panels are working their best, they must be monitored

- Generation is not obvious, therefore issues are not
- Small issues can heavily decrease power generation
- Solar Monitoring solutions exist, but can be expensive or reliant on others

Rubin York aims to create a simple sensor that can monitor a panel locally

- Traditional monitoring methods depend on third party companies
- The All-In-One Photovoltaic Sensor will be this product
- Able to measure and record generated voltage & current and a panel's temperature & irradiance

DESIGN GOALS & REQUIREMENTS

This project is a continuation of a previous Senior Design project, considering us to be Phase II. In Rubin's new vision, the following will be implemented.

The All-In-One PV Sensor (AIO PV Sensor) should be able to

- Withstand as much as 40 Volts, DC at 10 Amps
- Measure a Solar Panel's voltage, current, temperature and irradiance
- Transmit the 'Panel-Level' data wirelessly to a local node for data storage
- Connect via MC4 connections to be inserted in existing Solar Array strings

With these restraints, the AIO PV Sensor will accomplish

- Creating a simple sensor that can be installed on existing arrays
- Allowing OUC to have easy access to Panel-Level data
- Having a locally managed database for data analysis
- Reducing the reliance on third parties to read Panel-Level Data

SPECIFICATIONS

Sponsor Requirements

Requirement	Priority
Capable of handling & sensing 40 V, 10 A, DC.	High
Modular design for Temperature & Irradiance Sensing	High
MC4 Insertion or Connections	High
Wirelessly communicate with local node for data storage	High
About or below $20 per sensor	Moderate
Plastic enclosure capable of withstanding outdoors	Low
Year-long lifespan	Low

Engineering Requirements

Requirement	Constraint
Voltage Accuracy	±5% of actual value
Current Accuracy	±5% of actual value
Temperature Accuracy	±5% of actual value
Irradiance Accuracy	±5% of actual value
Data Transmission Interval	<10 seconds between datapoints
Wireless protocol	Self-Generated Wi-Fi or Bluetooth
PCB Power	Powered by Panel Generation, no external battery

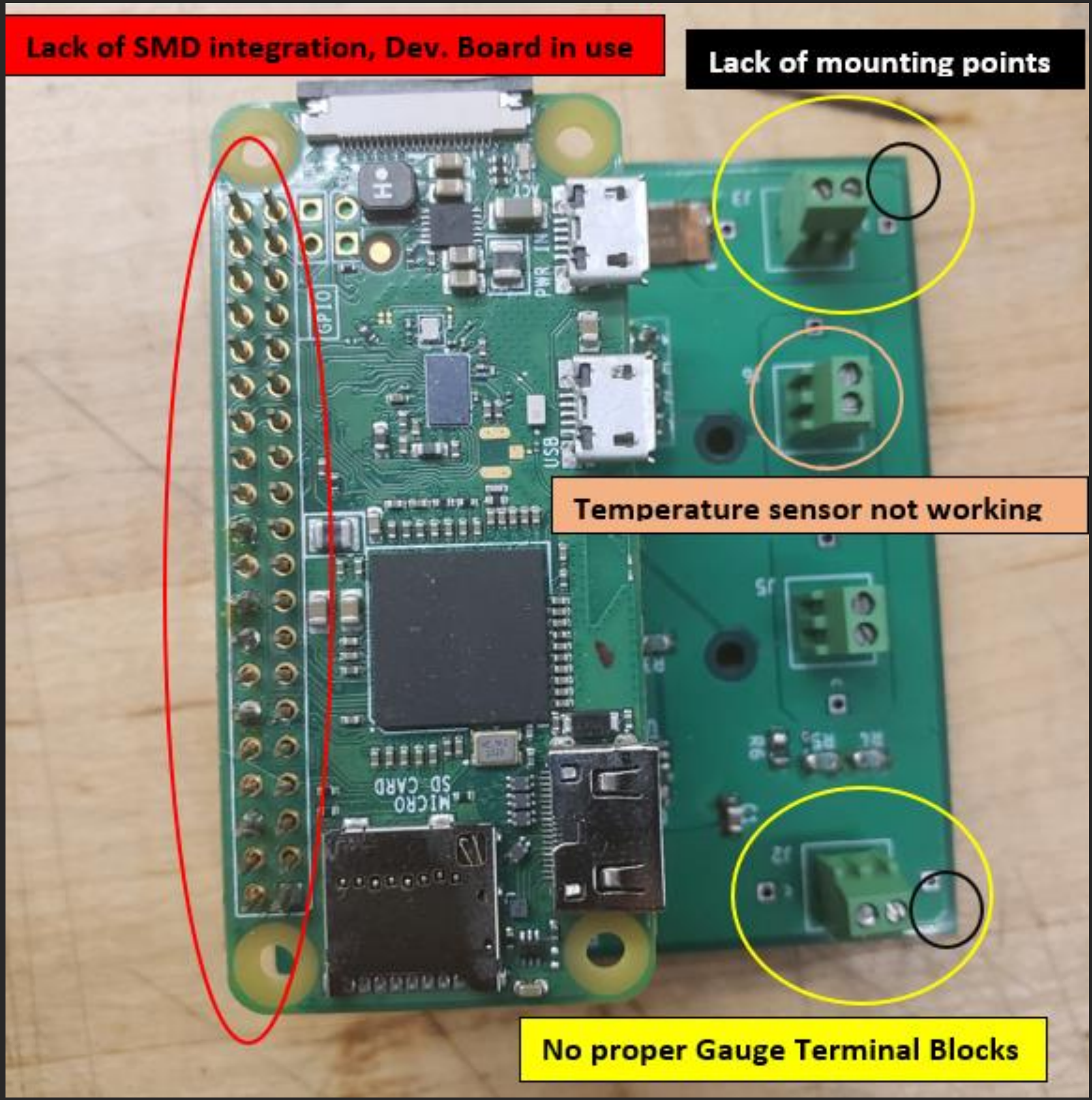
DESIGN APPROACH AND PROPOSED IMPLEMENTATION

Phase II design approach:

- Analyze Phase I attempt.
- Analyze phase I cost per unit assuming everything worked.
- Fixing or redesign "All-in-One-PV Sensor" design from phase I.
- Lower Research Cost by using Phase I Raspberry Pi 4 for the main data storage node.
- Research cost effective system components for every major sensor circuit.
  - Multifunction Integrated chips reduces board size and complexity.

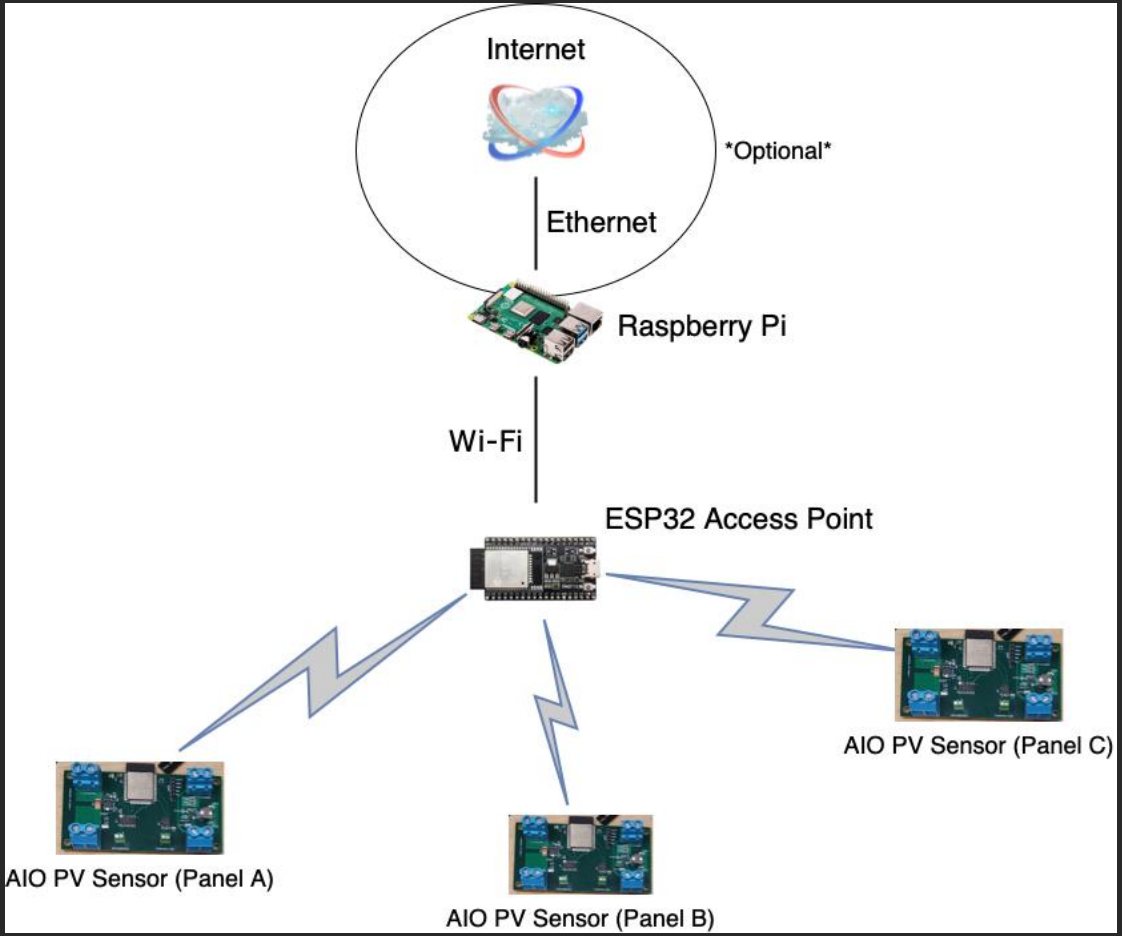
Phase II design Implementation:

- ESP-32 based sensing node for transmitting sensor data via WIFI and interpreting sensors input signal.

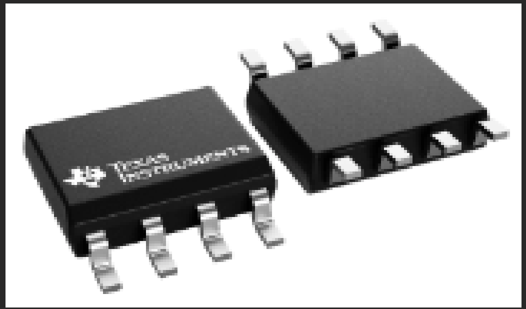


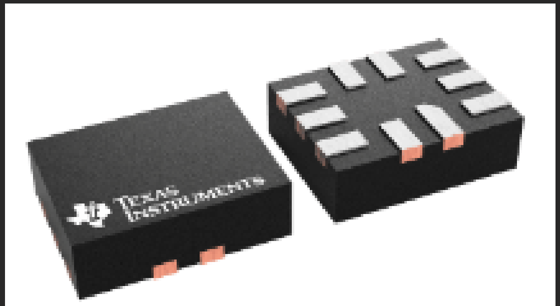
HARDWARE BLOCK DIAGRAM

Data is collected from each sensing component: thermocouple, pyranometer, voltage sensor, and current sensor. Once these devices have collected data, the ESP32 microcontroller will organize the data into a string which will then be sent to the Raspberry Pi microprocessor via a dedicated ESP32 access point and then parsed into a MySQL database.



SENSING AMPLIFIER





	TLV342A	INA216
Feature	Low-Voltage Rail-to-Rail	High precision current sense
Supply voltage	5.5 V < Vin > 1.5 V	5.5 V < Vin > 1.8 V
No. Op Amp	Two	One
Price	$0.323	$0.442

LOW-SIDE VS. HIGH SIDE

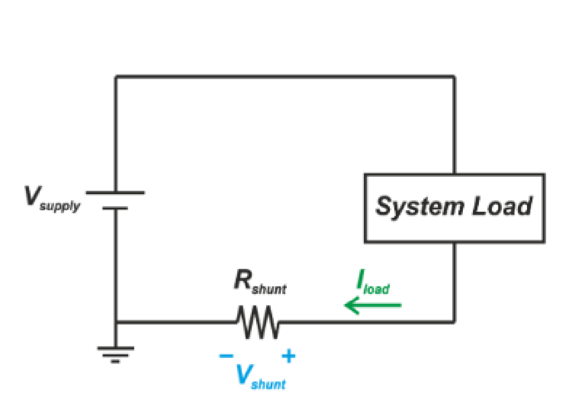
Low-side configuration for TLV342: IC is after the Load

Problems:
Offset voltage amplification
Ground disturbance

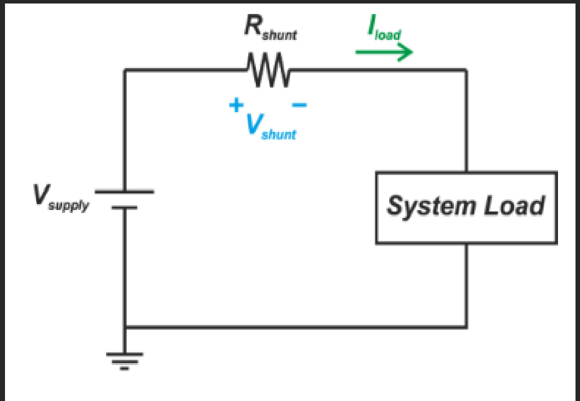
High-side replacement: IC is before ground

Problem:
High common mode voltage

Solution:
Current sensing amplifier

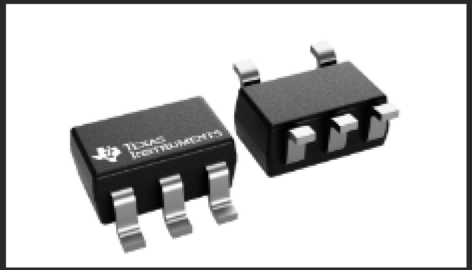


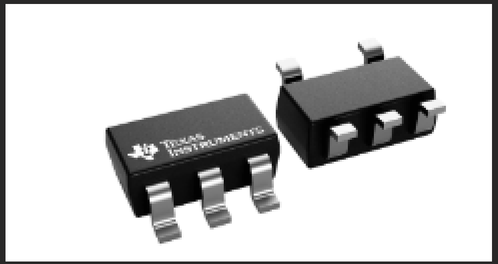
Low-side Configuration



High-side configuration

ALTERNATE CURRENT SENSING IC





	INA290	INA293
Feature	ultra-precise current sense amplifier	ultra-precise current sense amplifier
Supply voltage	2.7 V < Vin > 20 V	2.7 V < Vin > 20 V
Common mode voltage	2.7 – 120 V	-4 – 110 V
Offset voltage	12 µV	20 µV

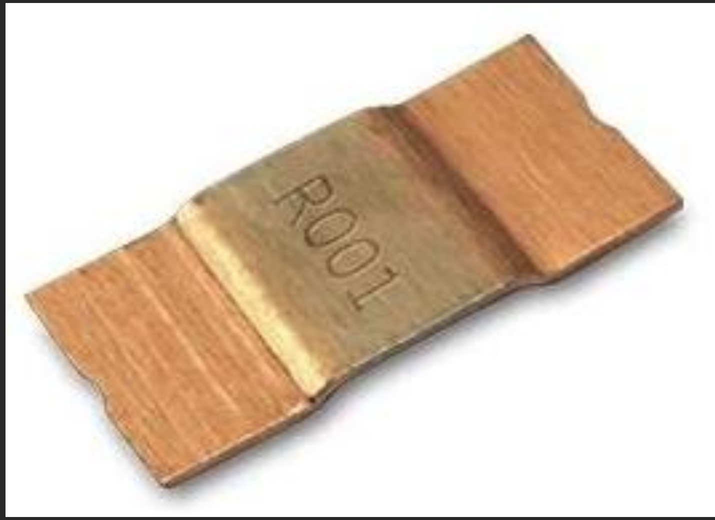
CURRENT SENSING

Current Shunt:

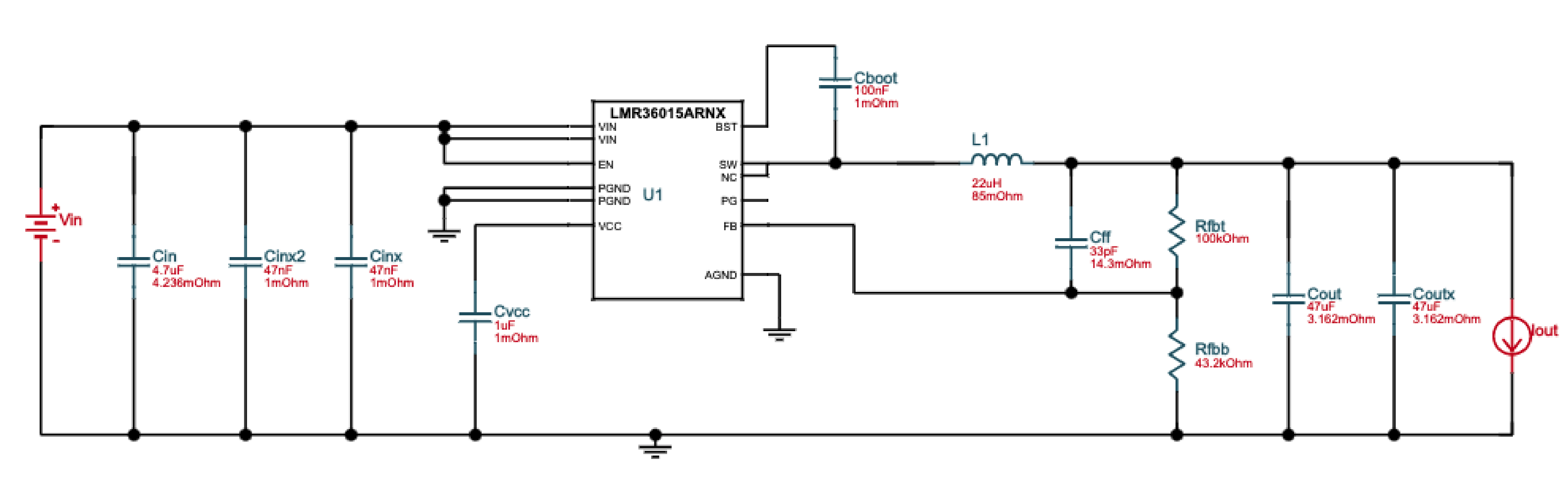
- One Milliohm shunt resistor
- Power Rating Of 4 W can handle 8.91 A

Voltage drop Across the Shunt is measured, and it is sent to ADC

Very small voltage drop to measure , therefore amplification is needed

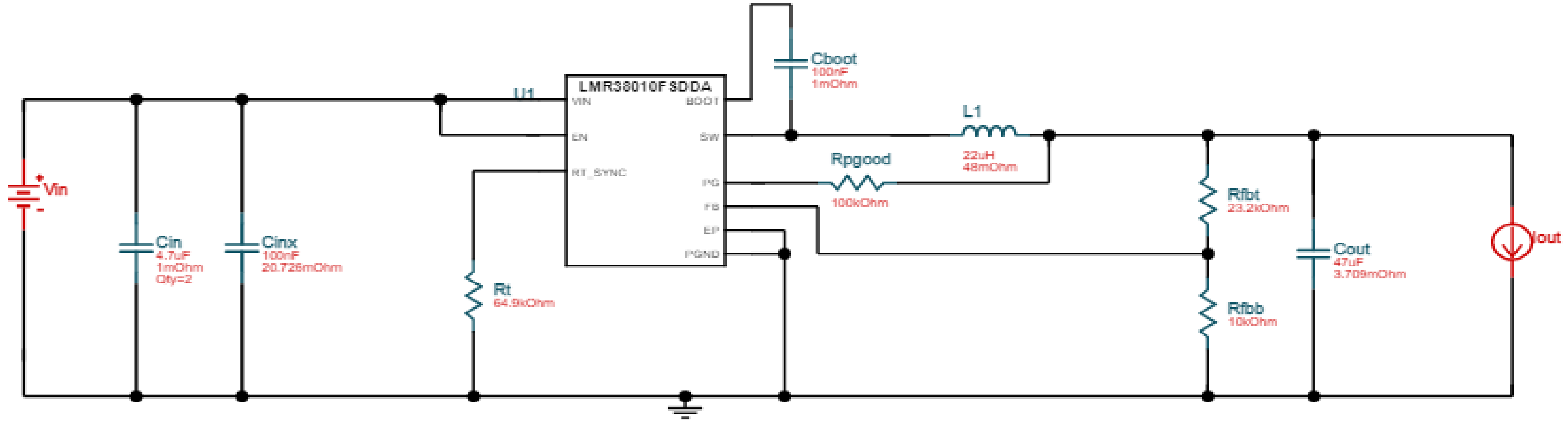


VOLTAGE REGULATOR-LMR36015



- 4.2 V – 60 V Buck Converter
- Supplies 3.3 V and up to 1.2 A
- Readily available for purchase

ALTERNATE DC TO DC-LMR38010

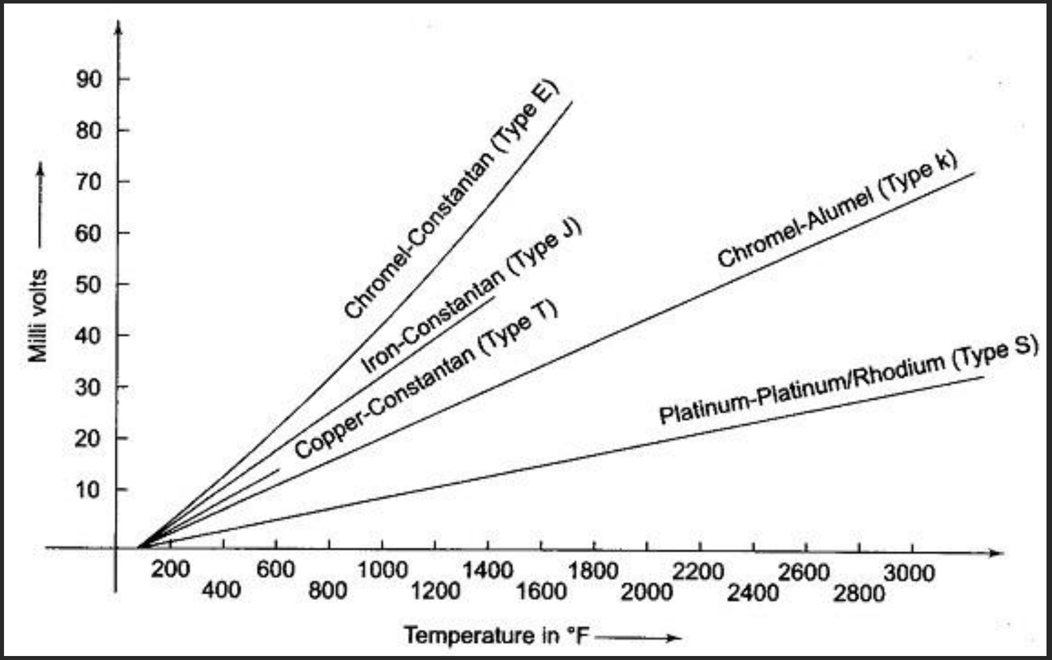


- 4.2 V – 85 V Buck Converter
- Supplies 3.3 V and up to 1 A
- Also, Readily available in the market

THERMOCOUPLE SELECTION

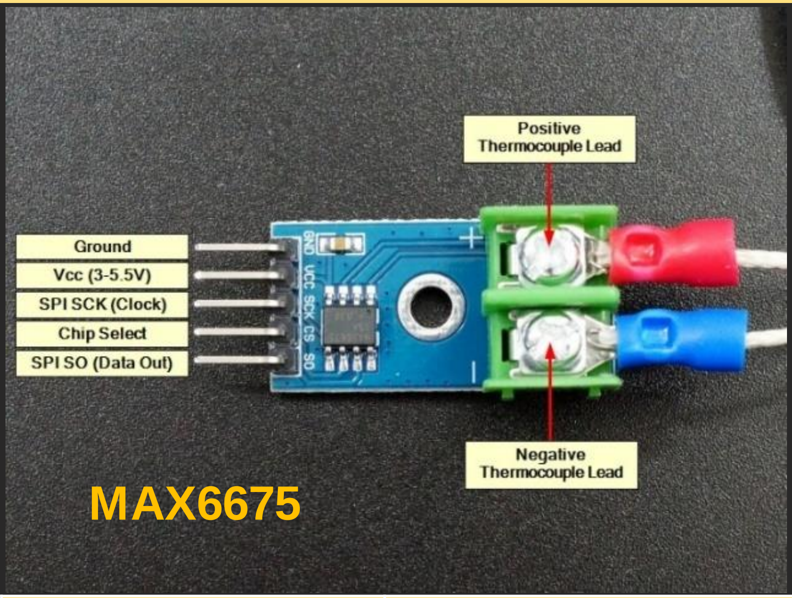
To select the best thermocouple, we can implement in our design we most take the following in consideration:

- Cost-effective with out mitigating performance.
- Fast Response Time.
- Easy to mount on solar cell without extra hardware.
- Highly Linearized for maximum accuracy.
- Weatherproof for outdoor use.



Type	Response Time	Operation Temperature Range	Material	Mount Option	Wire Insulation	Price
J	0.4 Sec.	0ºC to 1400 ºC	Iron-Constantan	N/A	PFA	$90.36
T	0.3 Sec.	0ºC to 600 ºC	Copper Constantan	Self-Adhesive	PFA	$83.99
E	0.2 Sec.	0ºC to 1600ºC	CHROMEGA™-Constantan	N/A	PFA	$100
K	0.3 Sec.	0ºC to 3500 ºC	CHROMEGA™-ALOMEGA™	Self-Adhesive	PFA	$83.98

THERMOCOUPLE SIGNAL CONDITIONING SELECTION



Conditioning System IC	Thermocouple Compatible	Resolution	ADC	Operational Voltage	Detection	Price
MAX6675	Type T and Type K	0.25ºC	14-bit	3V-5V	Open Circuit	$6
MAX31885	Type K, Type T, Type J, Type S, Type R, Type N, and Type E	0.0078125ºC	12-bit	3V- 3.6V	Short and Open Circuit	$17.50

IRRADIANCE SENSOR

For a sensor such as the All-In-One PV Sensor, a pyranometer is commonly used to measure irradiance.

For this application, the Pyranometer must be able to be removed with no impact to the primary functionality of the PCB. OUC decided that the cost of the pyranometer would not be considered in the final sensor cost.

Despite this, a cheap and self-standing solution was needed to successfully implement a pyranometer to our All-In-One PV Sensor.

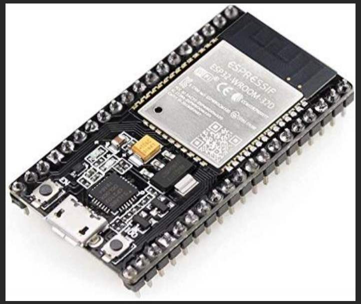
PYRANOMETER SELECTION

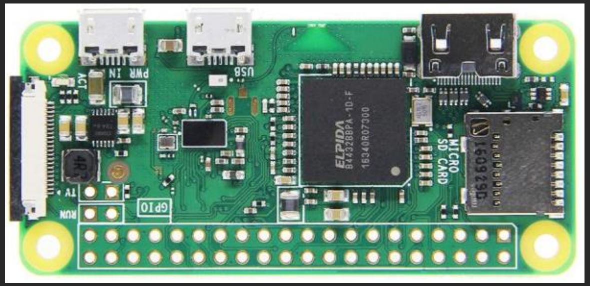
Pyranometer	SP-110-SS	SP-510-SS	CS320
Technology	Silicon-Cell	Thermopile	Thermopile
Output	Analog, ~100mV	Analog, ~400mV	Digital Signal
Power Supply	Self-Powered	Self-Powered	6~24 VDC
Response Time	<1ms	0.5 s	2 s
Average Cost	$230	$330	$524

PYRANOMETER IMPLEMENTATION

Pyranometer	MAX4194	MCP3008	INA126
Technology	Instrumentation Amplifier	Pseudo-Differential ADC	Instrumentation Amplifier
Voltage Supply	2.7 – 7.5 V	2.7 – 5.5 V	0 – 36 V
Current Supply	93µA	500µA maximum	10 mA
Output	Voltage, 0-3V	Digital Signal	Voltage, 0-3V
Average Cost	$6	$3	$4

MICROCONTROLLER IMPLEMENTATION

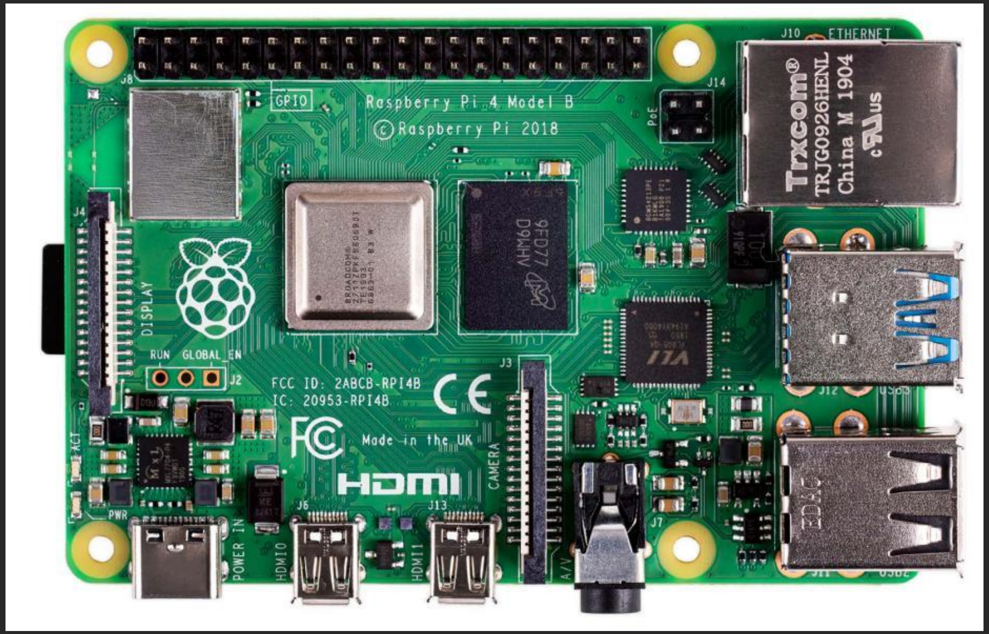




Microcontroller	ESP32	Raspberry Pi Zero
CPU	Xtensa single-core 32-bit LX6 microprocessor, 240Mhz	Broadcom BCM2835 1Ghz, Single-core
RAM	520KB	512MB
Wi-Fi/Bluetooth	Yes	Yes
Power	3.3V or 5V, supplied via GPIO pins or 5V, supplied via micro USB connector	5V, supplied via micro USB connector
Average Cost	$5	$10

MICROPROCESSOR IMPLEMENTATION

The microprocessor we chose for our design is the Raspberry Pi 4 Model B+. The Raspberry Pi features everything we need for our design, such as a programmable operating system, Wi-Fi and Ethernet, HDMI/video ports, and USB. Additionally, with a microSD port for the main storage, the Raspberry Pi can utilize up to 2 TB of storage. For our purposes, we have chosen a 128 GB microSD card that stores our operating system and MySQL database with over 100 GB to spare for years' worth of datapoints.

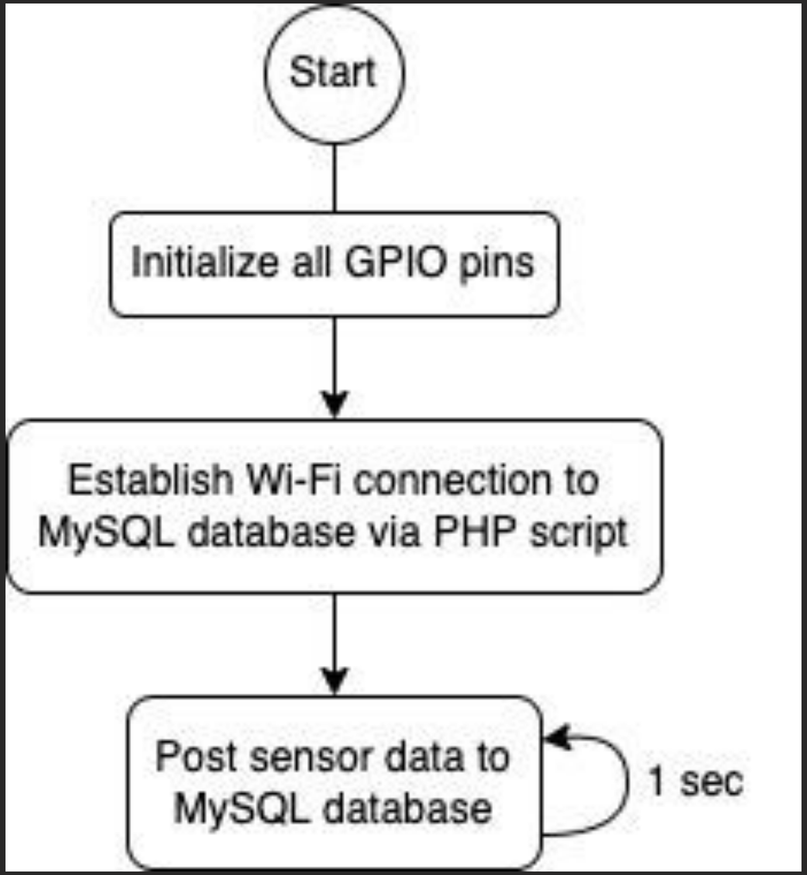


MICROCONTROLLER PROGRAM FLOW

At the start of the ESP32's C code, each GPIO pin that will be used to transmit data from the collecting sensors to the microprocessor will be initialized.

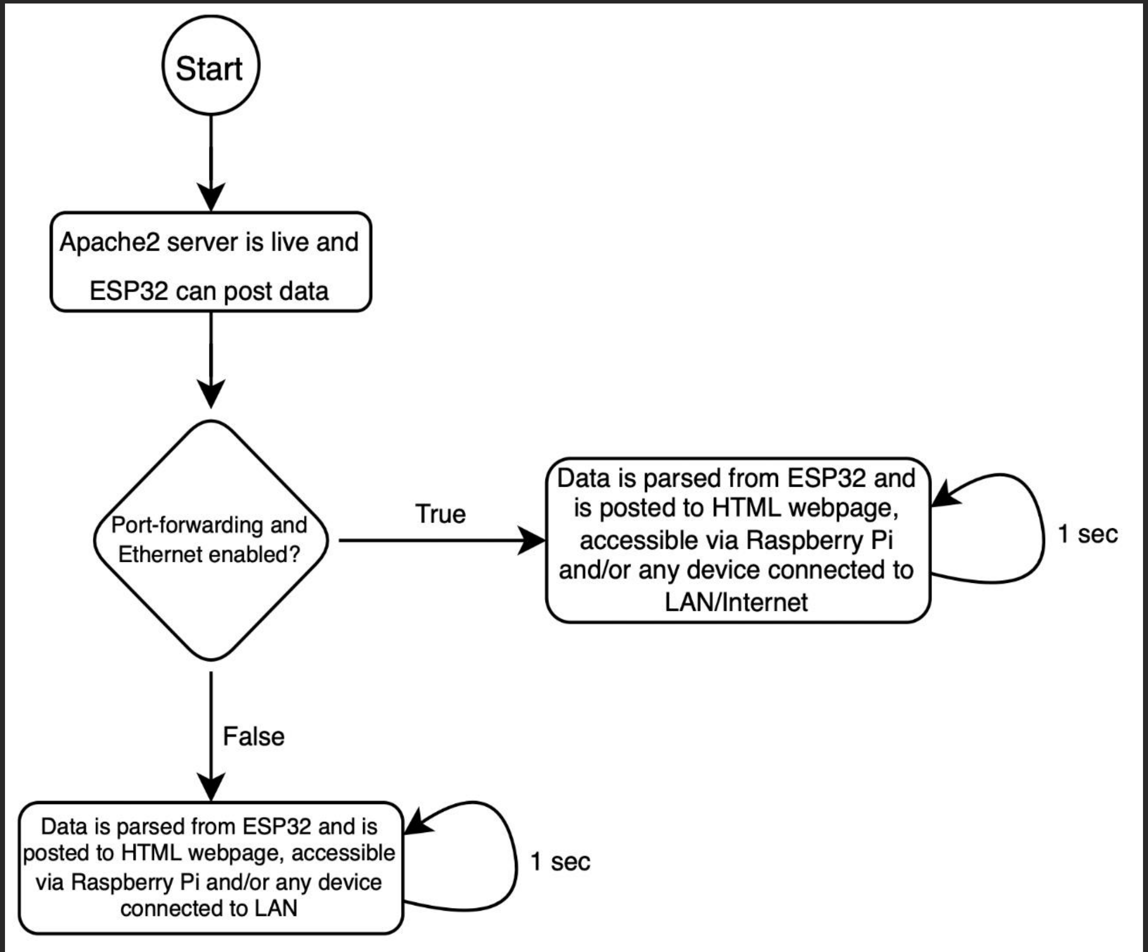
Next, the ESP32 establishes a Wi-Fi connection to the microprocessor's MySQL database via a PHP script.

Finally, the ESP32 will post collected data to the microprocessor's MySQL database until powered off.



MICROPROCESSOR PROGRAM FLOW

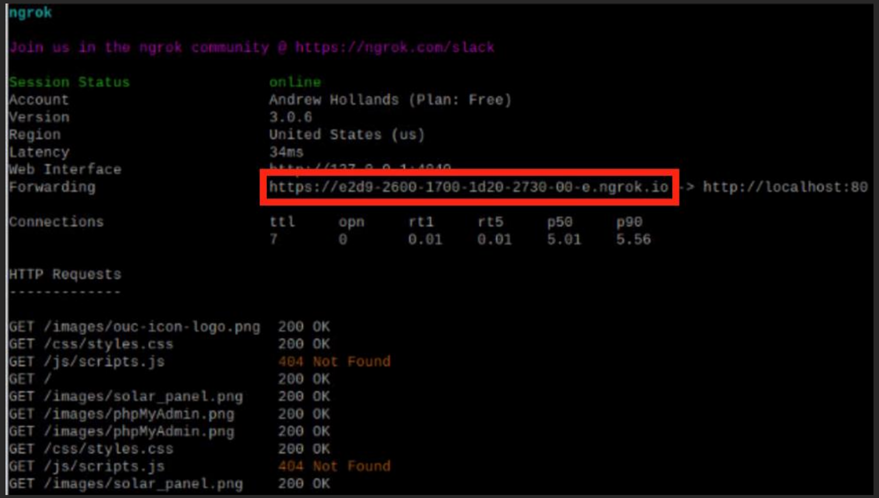
The Raspberry Pi will house multiple programs to support the wirelessly connected AIO PV Sensor. The software bundle installed on the microprocessor can be referred to as a LAMP (Linux, Apache, MySQL, PHP) server. The LAMP server uses each of its components in tandem to be able to wirelessly receive and post collected data to an HTML webpage, which is stored locally. It is called a LAMP server because the **L**inux operating system controls the **A**pache server and data is queried using **M**ySQL and **P**HP scripting.

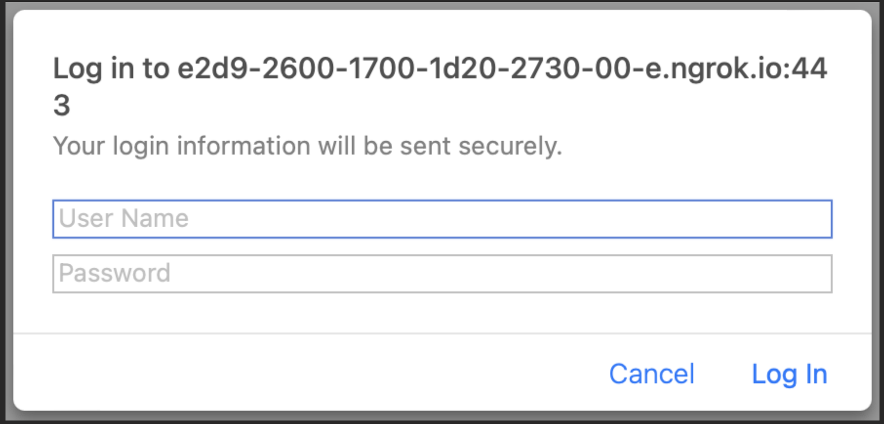


MICROPROCESSOR PROGRAM FLOW, CONT'D

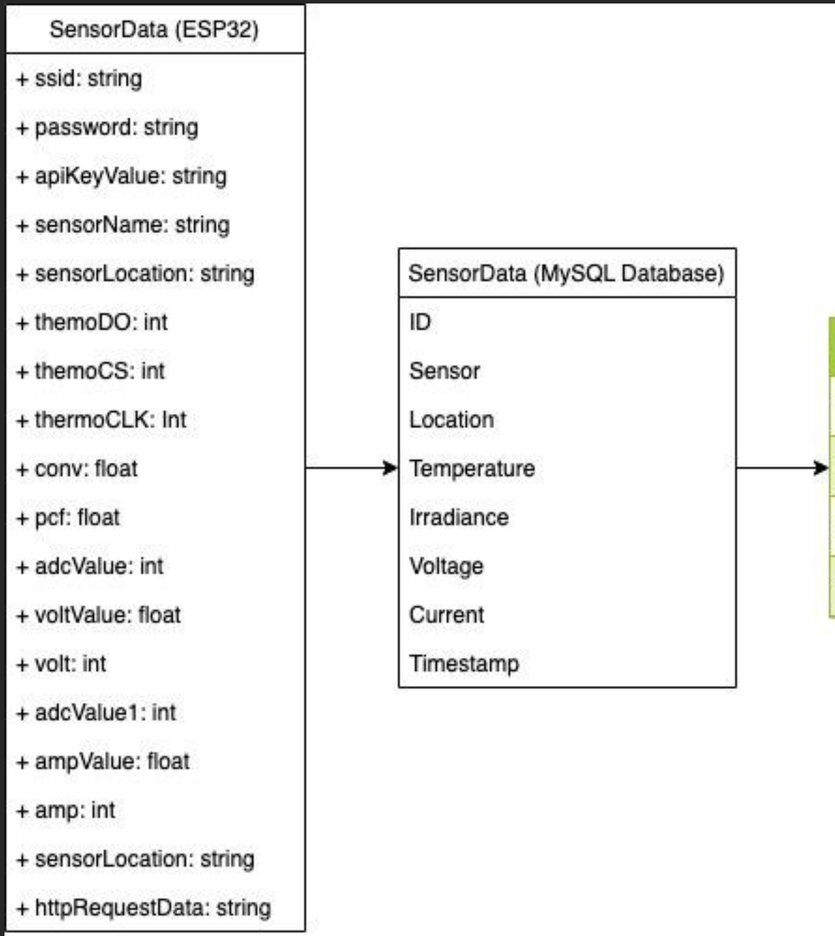
Additionally, the Raspberry Pi has built-in functionality to enable [or disable] a local directory to be ported to the Internet when connected to ethernet through a free port-forwarding service called ngrok.

The client can enable port forwarding with ngrok and view session statistics and its unique and secure HTTP URL, which is accessible only through specified credentials. When the client no longer wants to forward their local directory to the Internet, they can easily disable it by closing the Terminal window.





MICROPROCESSOR PROGRAM FLOW, CONT'D

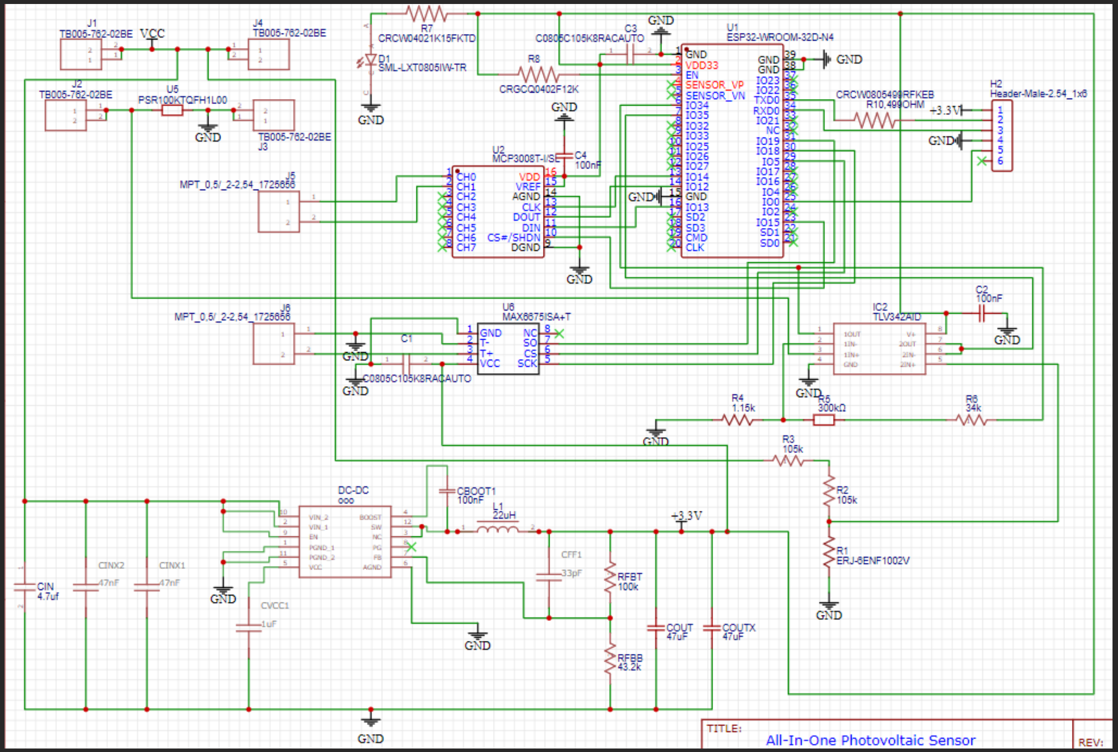


ID	Sensor	Location	Temperature (°C)	Irradiance (W/m^2)	Voltage (V)	Current (A)	Timestamp
1	AIOPVSensor1	SolarPanel1	32.50	62.8	35.5	6.30	2022-04-15 08:00:12
2	AIOPVSensor1	SolarPanel1	32.25	62.9	35.1	6.31	2022-04-15 08:00:13
3	AIOPVSensor1	SolarPanel1	32.00	63.1	35.4	6.24	2022-04-15 08:00:14
4	AIOPVSensor1	SolarPanel1	31.50	63.5	35.3	6.5	2022-04-15 08:00:15

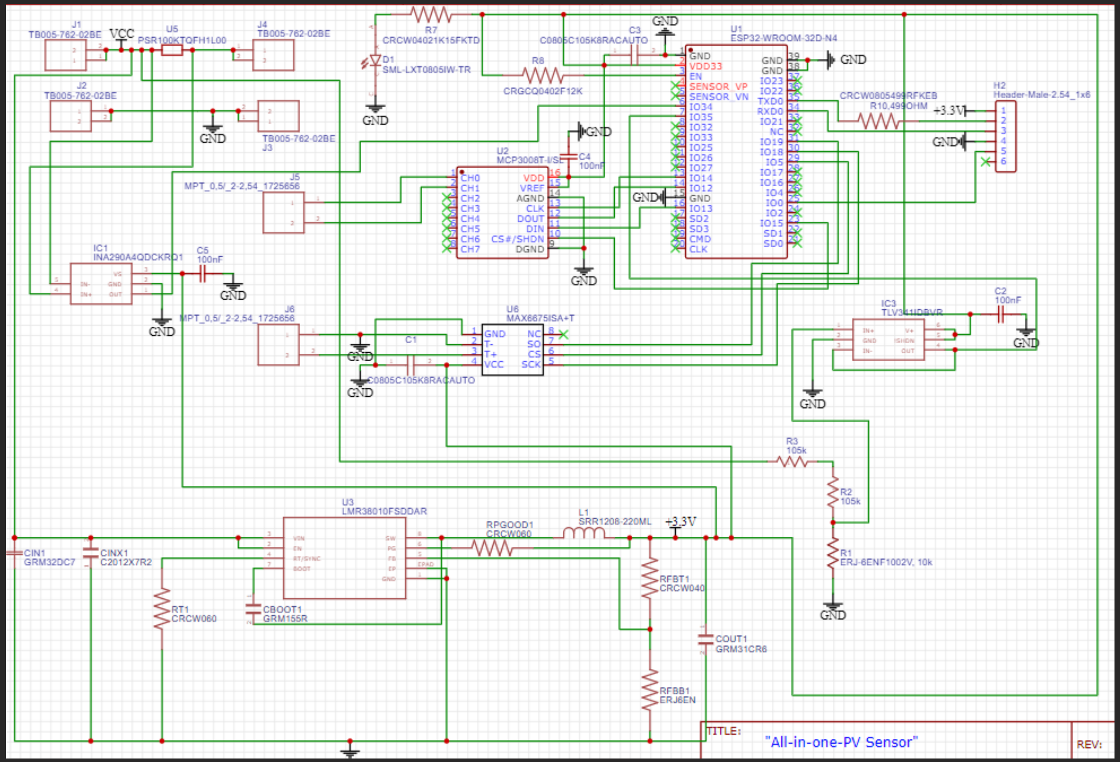
MICROPROCESSOR DIFFICULTIES

There were some difficulties encountered along the way of designing the software running on the Raspberry Pi. Those difficulties include being unable to set a static IP address. We sought to set a static IP address for the Raspberry Pi so our ESP32 could easily access post data to the Raspberry Pi without having to modify the IP address included in the ESP32's code. Additionally, we ran into some issues with modifying the SQL query code to add additional columns for more datapoints.

REVISED SCHEMATICS FOR V2 & V3



V2.0 Schematic Low side current sensing



V3.0 Schematic High side current sensing

CURRENT SENSING

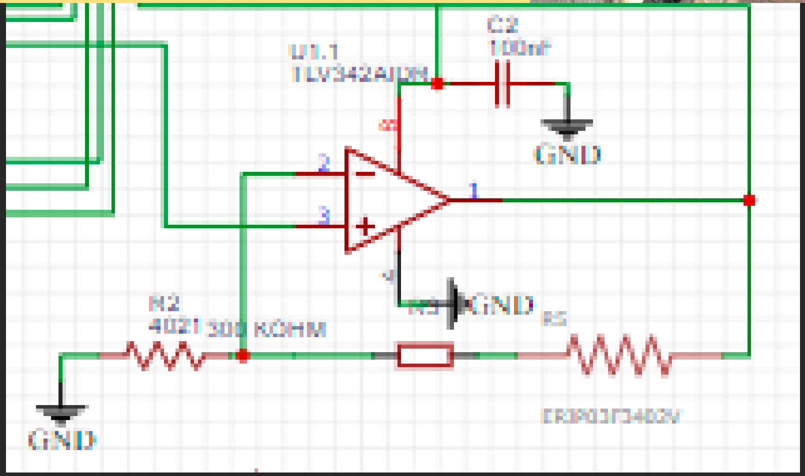
Noninverting Differential gain amplifier:

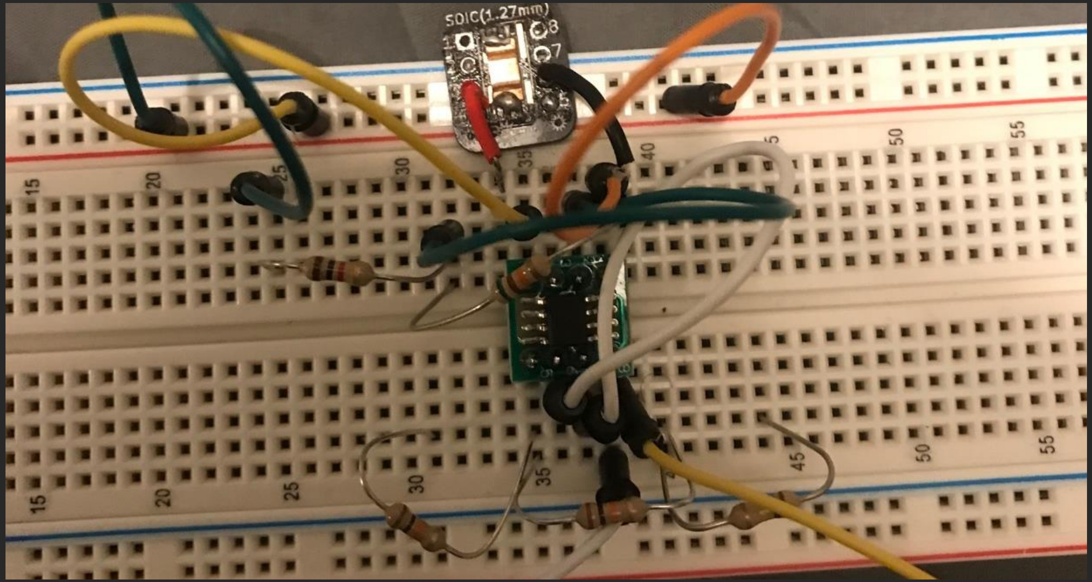
- Amplifies Shunt Voltage
- Rin = 1.15 KΩ
- Rf = 139 KΩ
- Av = 122
- Voltage sent to the ADC

Differential amplifier gain:

- Amplifies shunt voltage
- Av = 100

Ohms Law will be used to obtain current value





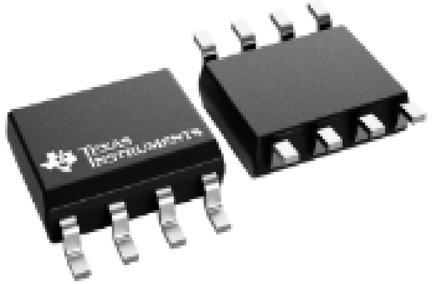
CURRENT SENSING IMPROVEMENT

- TLV342 had too high of an offset voltage.

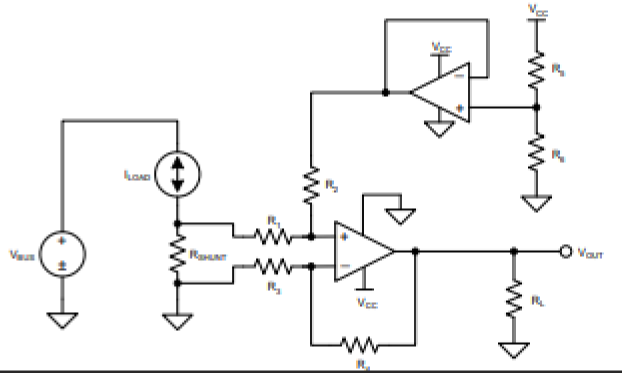
- This caused the gain to vary and the noise to be amplified

- Solution:
- OPA2330, offers small offset voltage (35 µV)

- Achieve better current sensing



Bidirectional, Low-Side Current Sense



VOLTAGE MEASURING

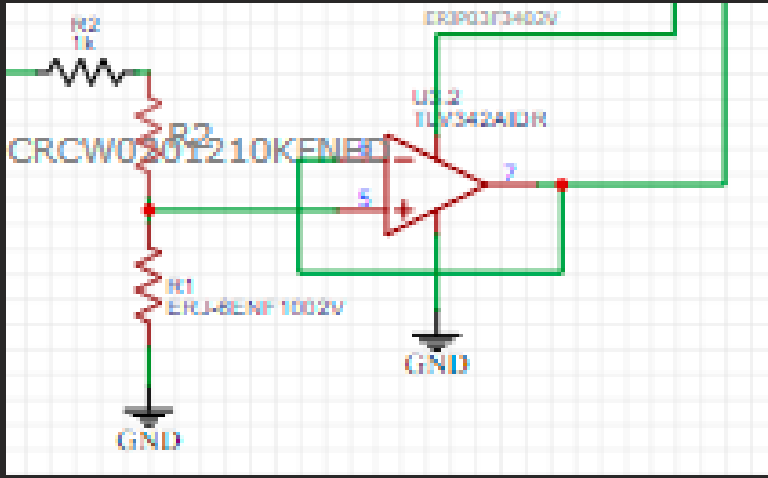
Voltage leaving solar panel is too high.

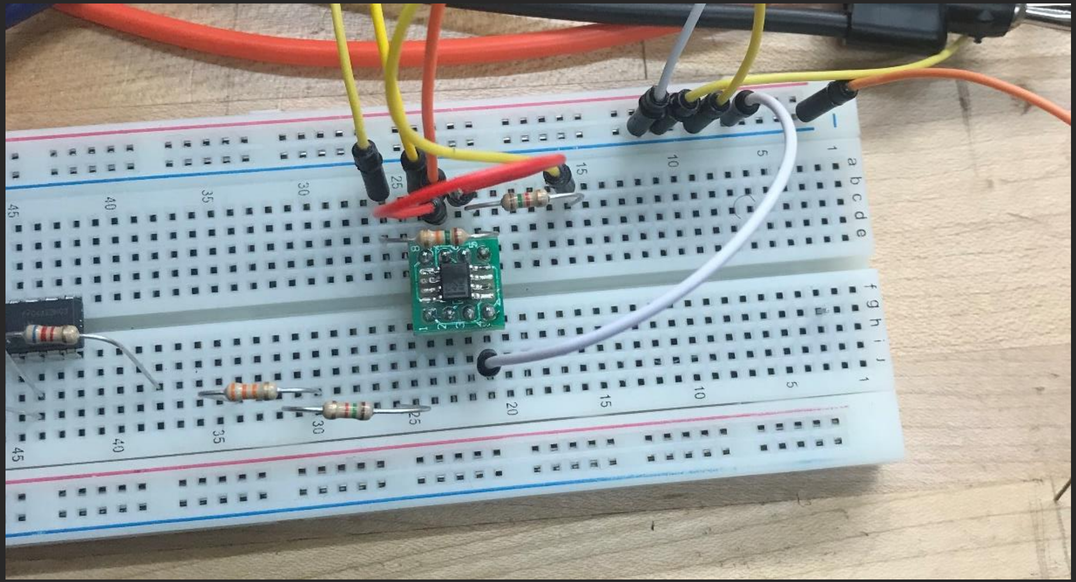
Voltage divider:

- Reduces 39 V to 1.77 V
- R1 = 105 KΩ (*2)
- R2 = 10 KΩ

Unity gain buffer:

- Reduces Power consumption
- Reduces Noise





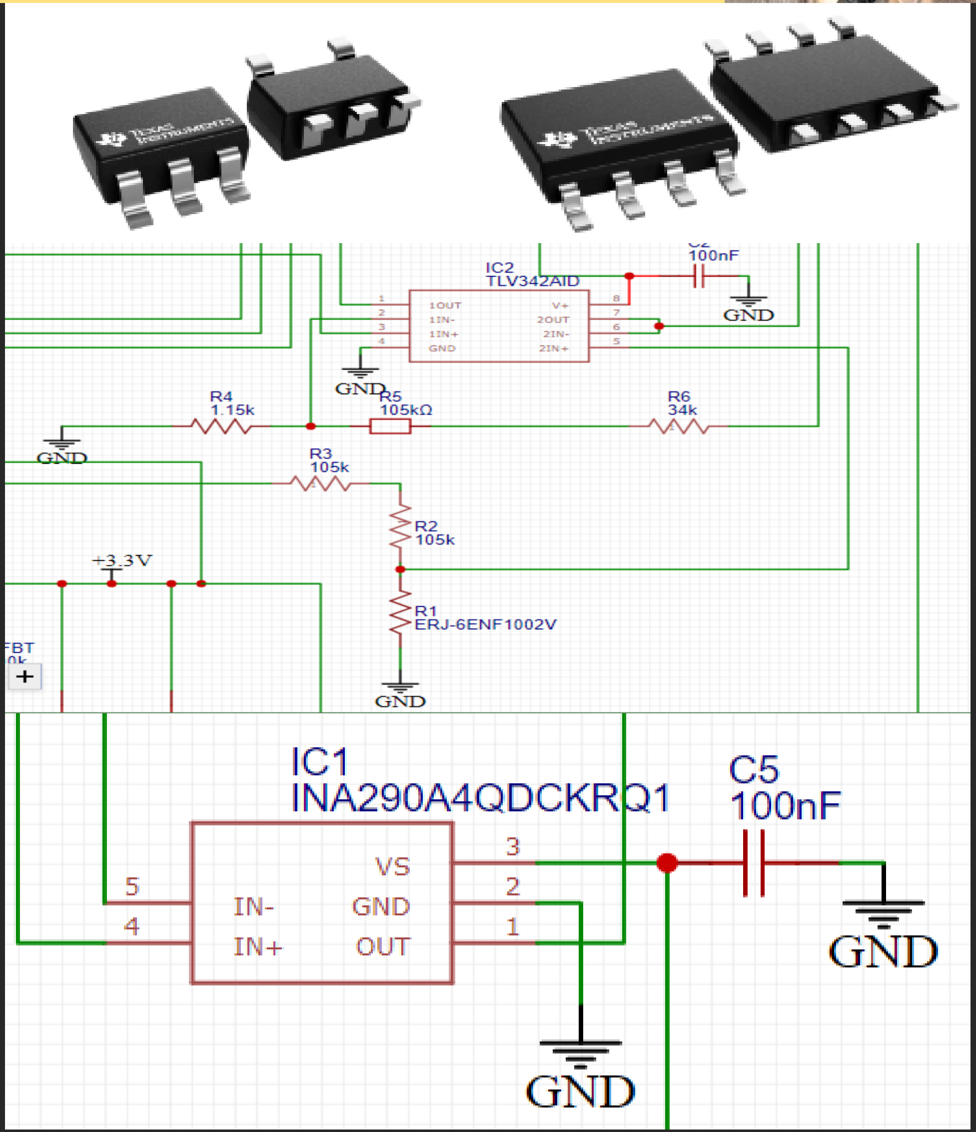
CURRENT AND VOLTAGE SENSING PCB IMPLEMENTATION

The TLV342 will have application in both the current and voltage sensing on the PCB.

Gain Resistors would amplify the voltage across the shunt, which would then be sent to the ADC of the ESP 32.

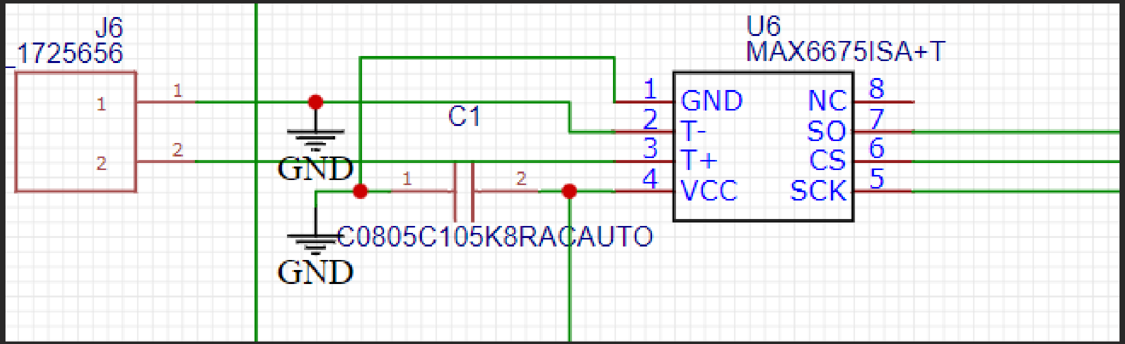
Voltage divider reduces voltage for measuring, then unity gain buffer will send the voltage to the ADC of the ESP32.

ESP32 send Data collected to a node.

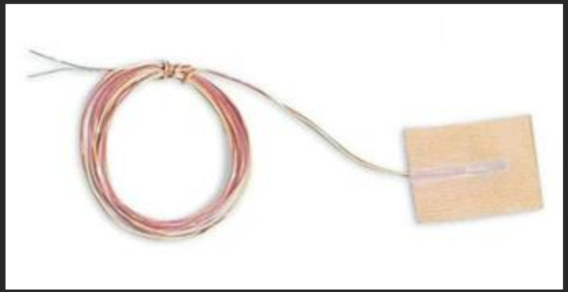


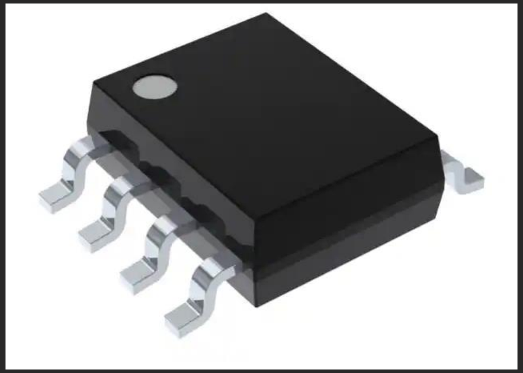
TEMPERATURE PCB IMPLEMENTATION

The MAX6675 was the most cost-effective component that we could use in our implementation that does not compromise thermocouple compatibility and resolution.



Even if only has 12-bit digital resolution, compared to the MAX31885. MAX6675 has a 0.25ºC resolution that falls within require +/- 10% temperature offset.





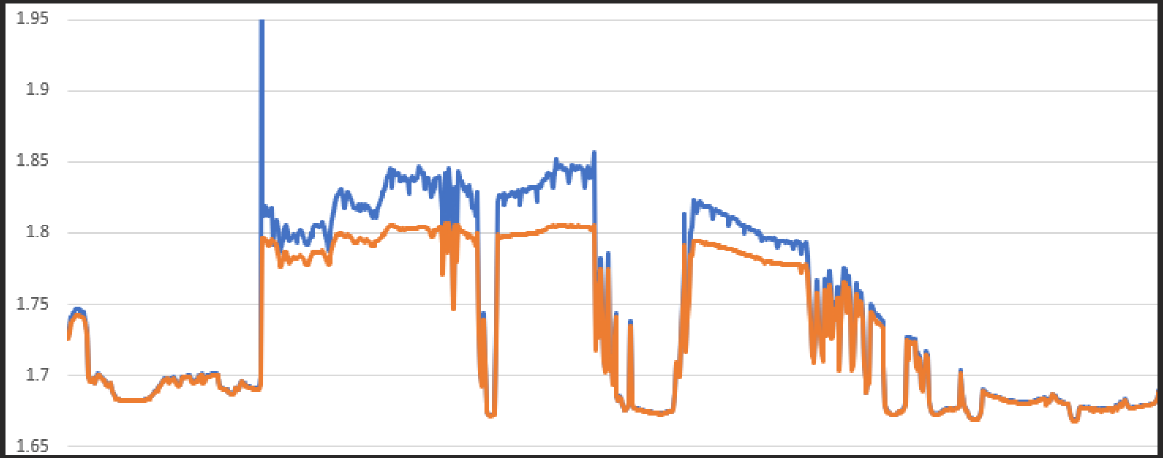
The thermocouple utilized in this application is both a Type T and Type K thermocouple self-adhesive.

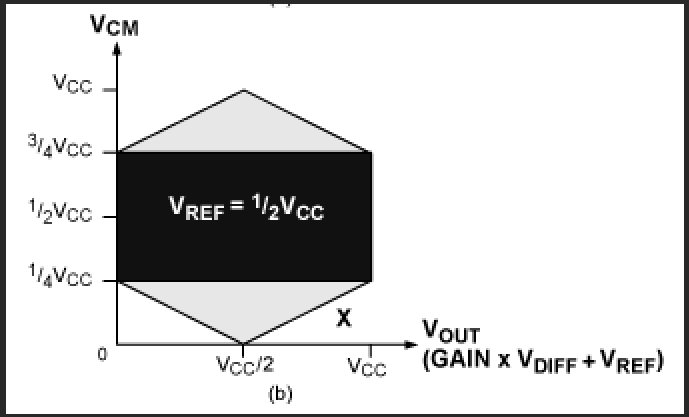
IRRADIANCE IMPLEMENTATION DIFFICULTY

Initially, the MAX4194 was selected to amplify the pyranometer's signal to send to the ESP32's on-board ADC.

The datasheet was misleading, as the part advertised full functionality under a single supply. Due to the pyranometer's low and differential output, the signal could not properly be amplified without saturation.

Early tests showed that when operating on a single supply, the measured irradiance error grows as exposure to sunlight increases due to low comparative voltages.



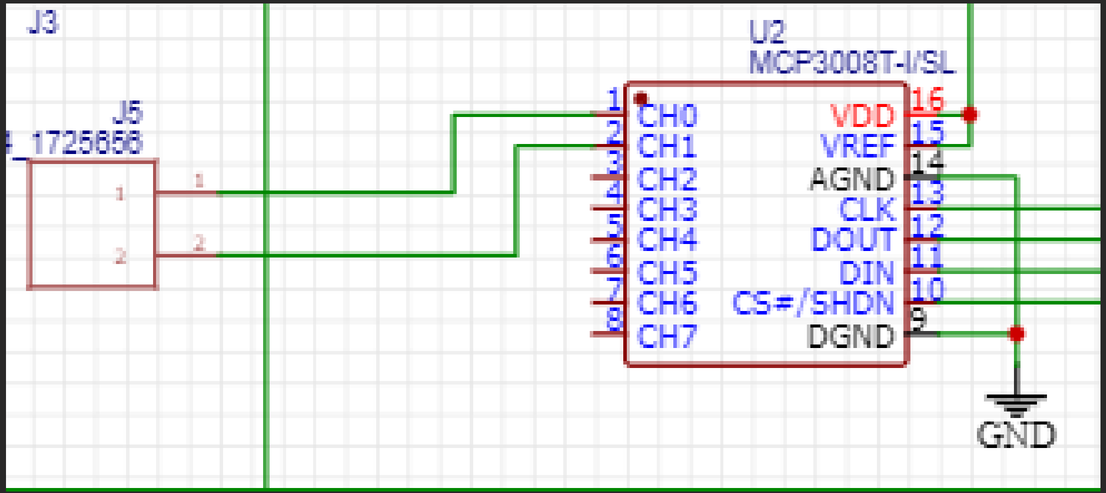


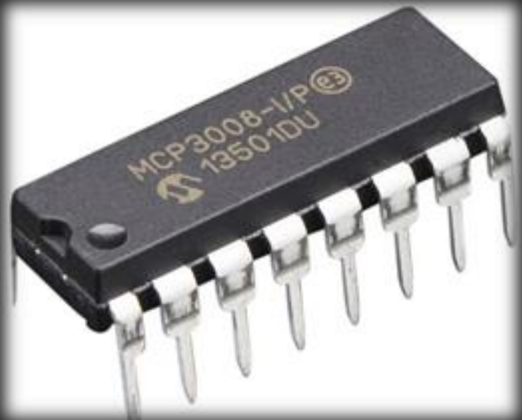
IRRADIANCE PCB IMPLEMENTATION

The MCP3008 was selected as the most practical and affordable option to integrate the SP-110-SS Pyranometer into the PCB.

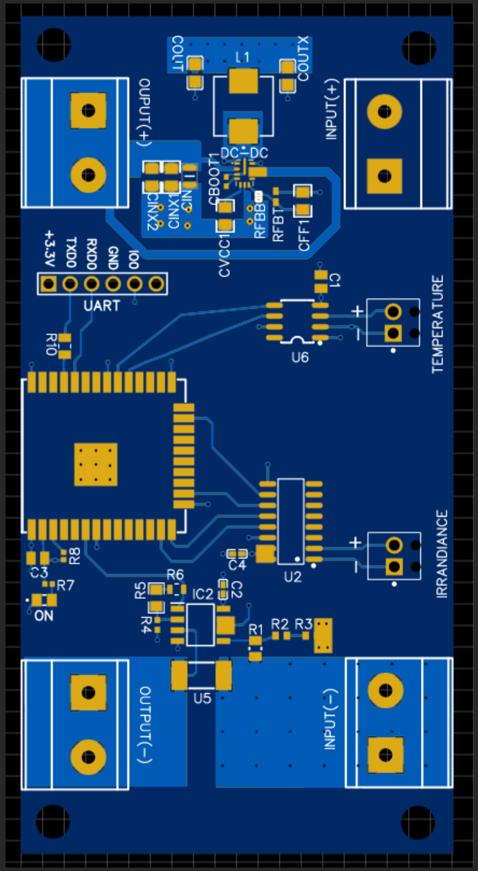
Although it has a 10-bit resolution, it offers a pseudo-differential input reading and a low price point combined with high part availability. The pseudo-differential input allows the differential signal to be easily translated into a digital one.

This choice cut the price of integrating the pyranometer by half and greatly simplified the means of translating the signal to digital.

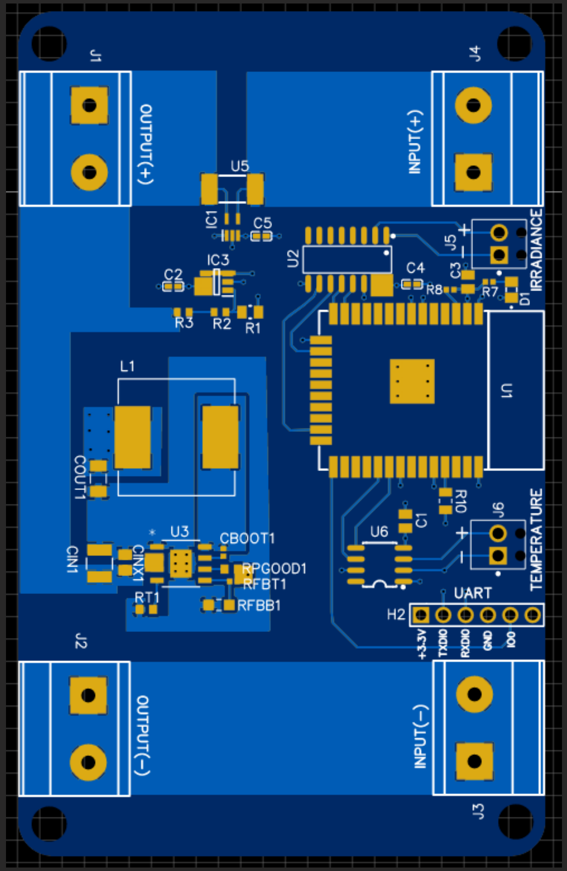




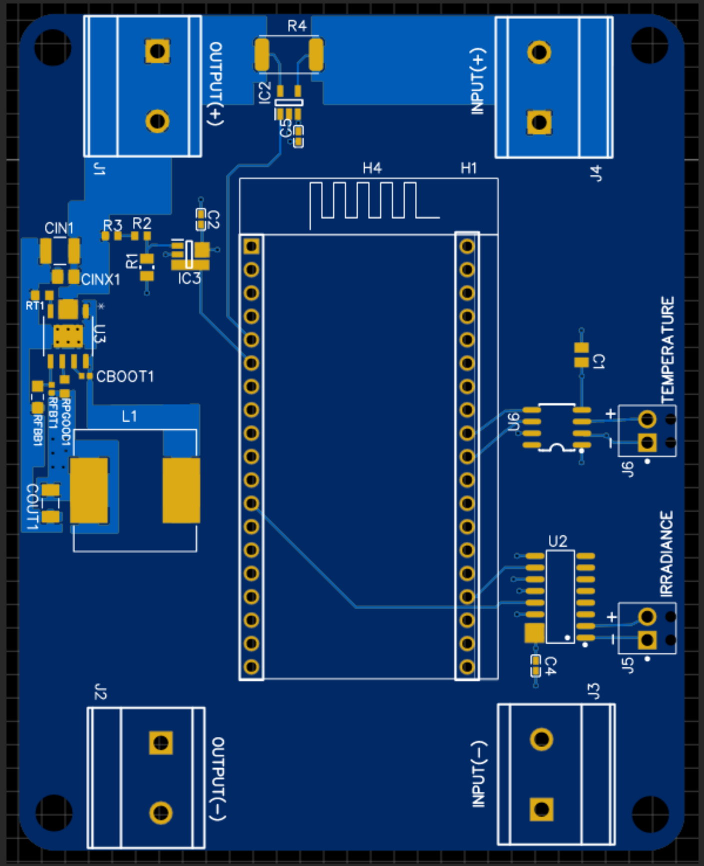
PCB VERSIONS & LAYOUTS



Version 2



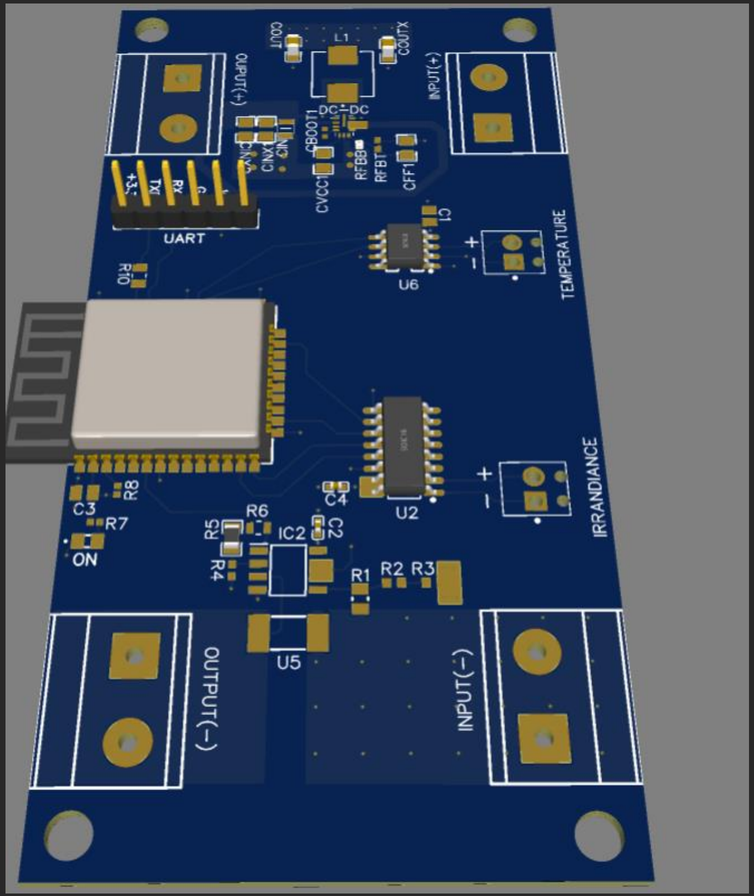
Version 3, SMD Edition

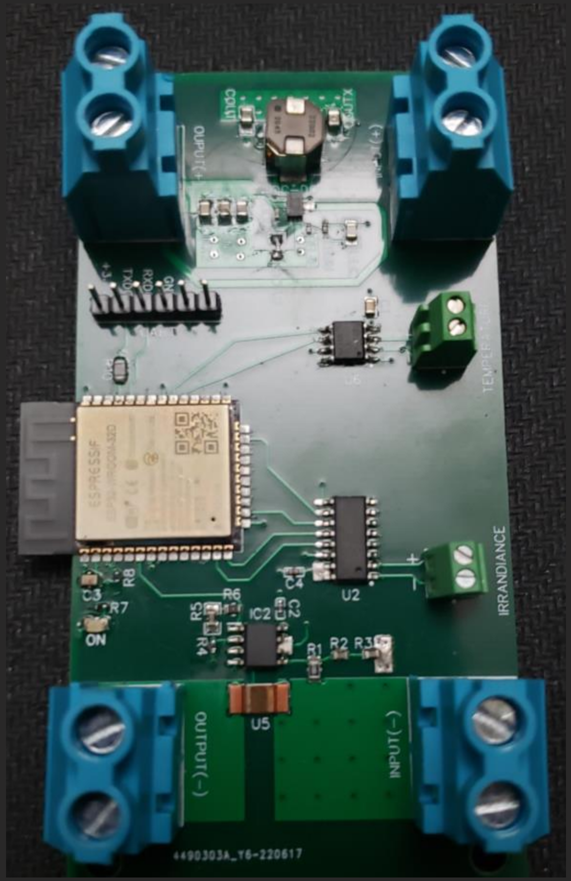


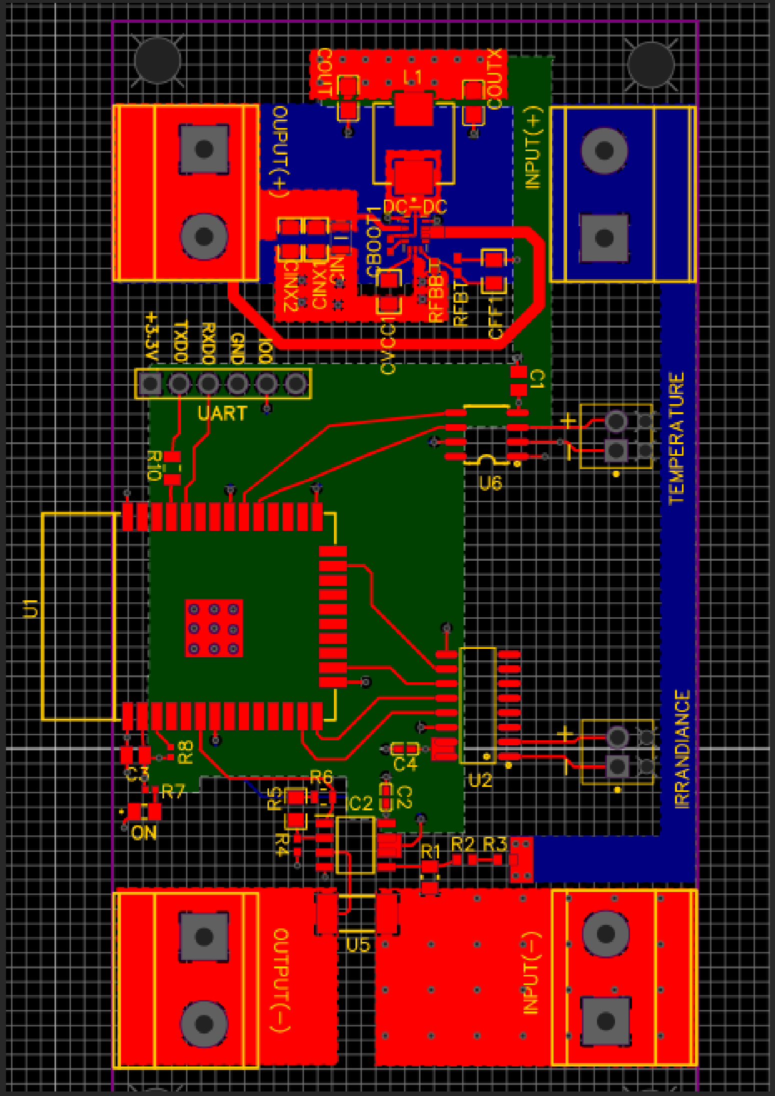
Version 3, Dev-Board Edition

VERSION 2 PCB - SMD

- Low Side Currenting and voltage Sensing with a single IC.
- Small profile DC-DC Stepdown Converter
- 4-layered PCB to minimized noise and heat dissipation.

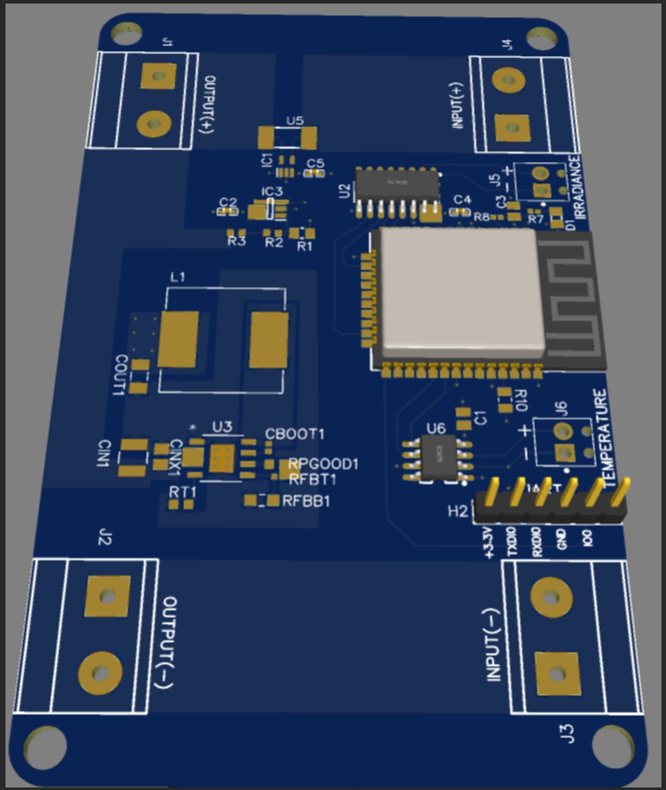


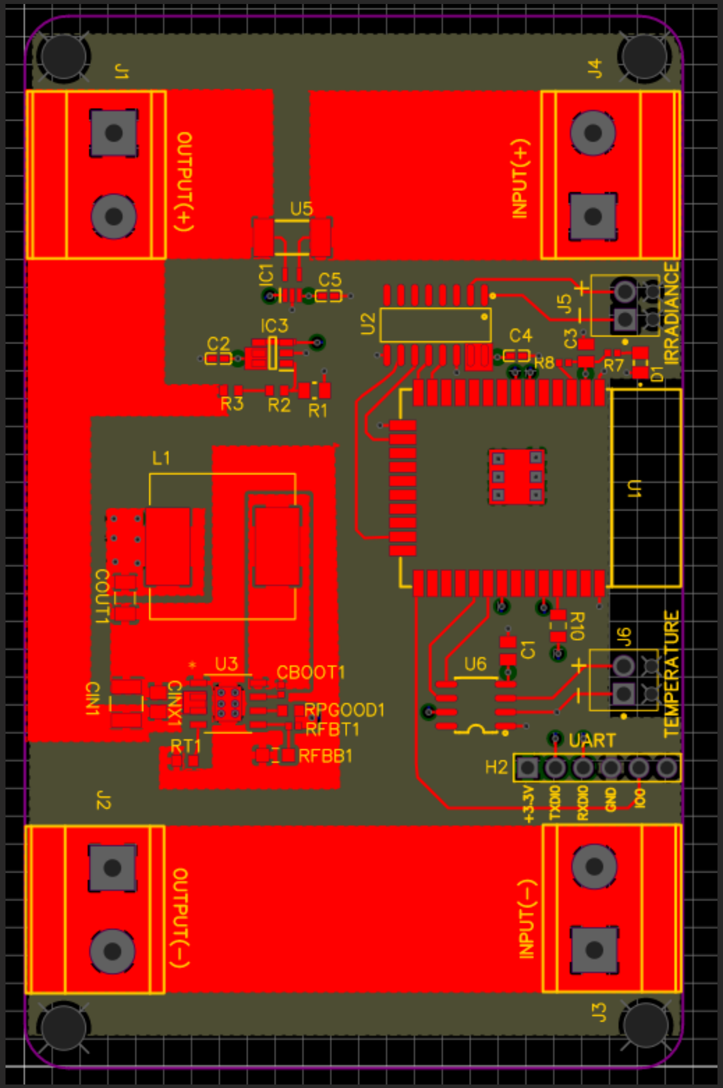




VERSION 3 PCB - SMD

- Bigger profile DC-DC Stepdown Converter with underside ground pad for heat dissipation.
- 4-layered PCB to minimized noise and heat dissipation.
- High Side current Sensing to improve current resolution.

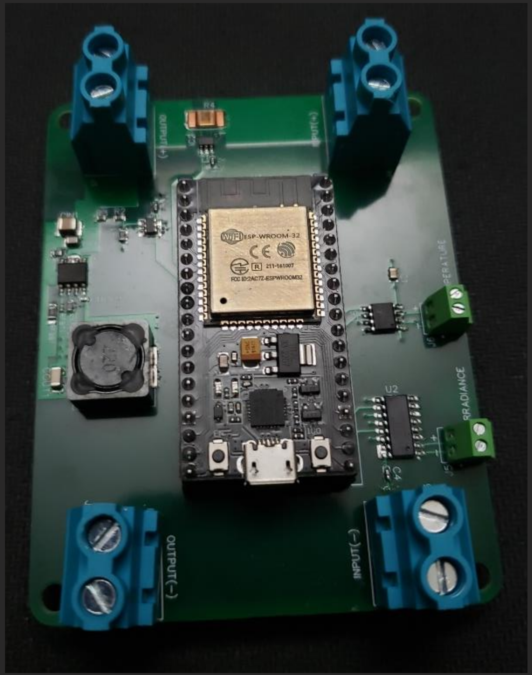


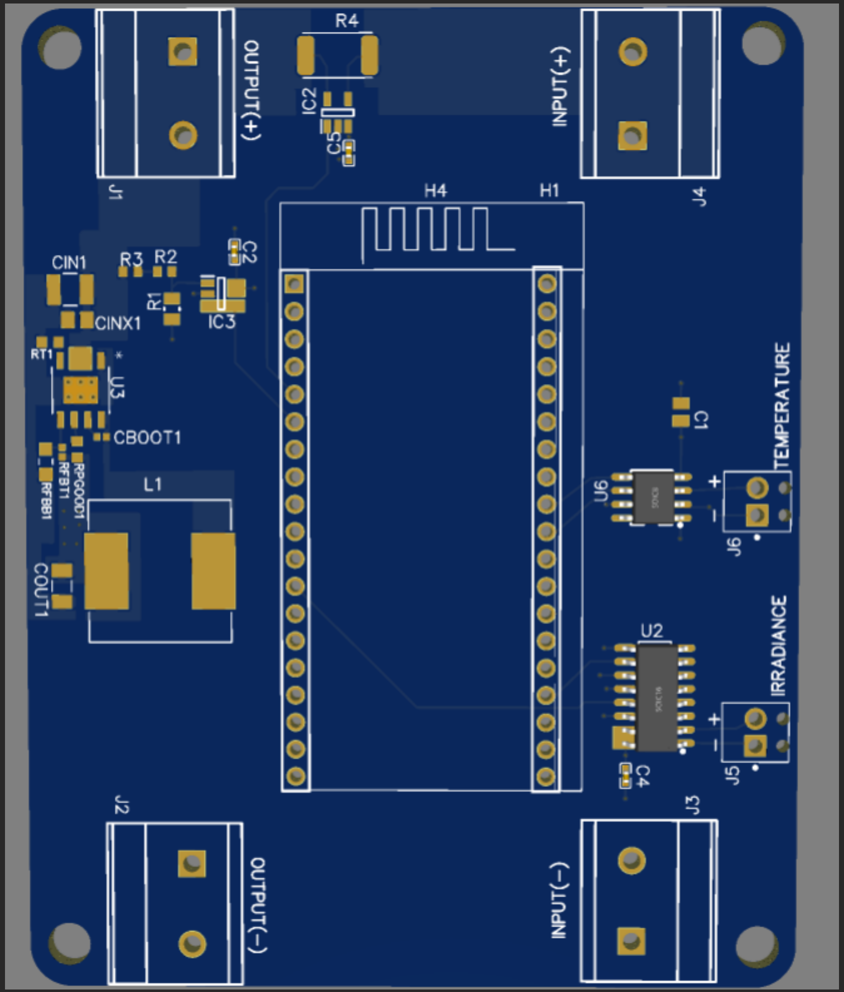


VERSION 3 PCB - DEVBOARD

For the Third Version of the “All-one-PV Sensor” we decided to implement an ESP-32 developmental board as a test model. This was done for primarily for:

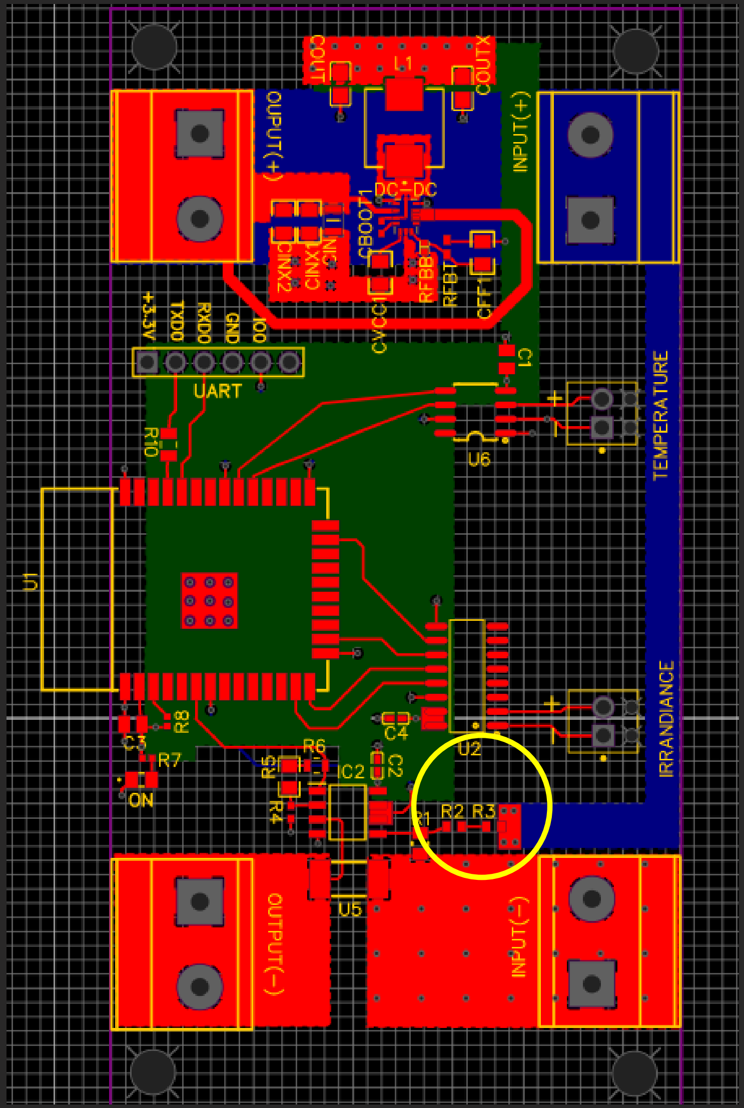
- Stress testing the DC-DC Stepdown Converter with higher-than-normal voltages and currents to test the designs limitations,
- Ease of multipoint probing.
- Allows ease of ESP-32 replacement incase of failure due to stress testing on the field.





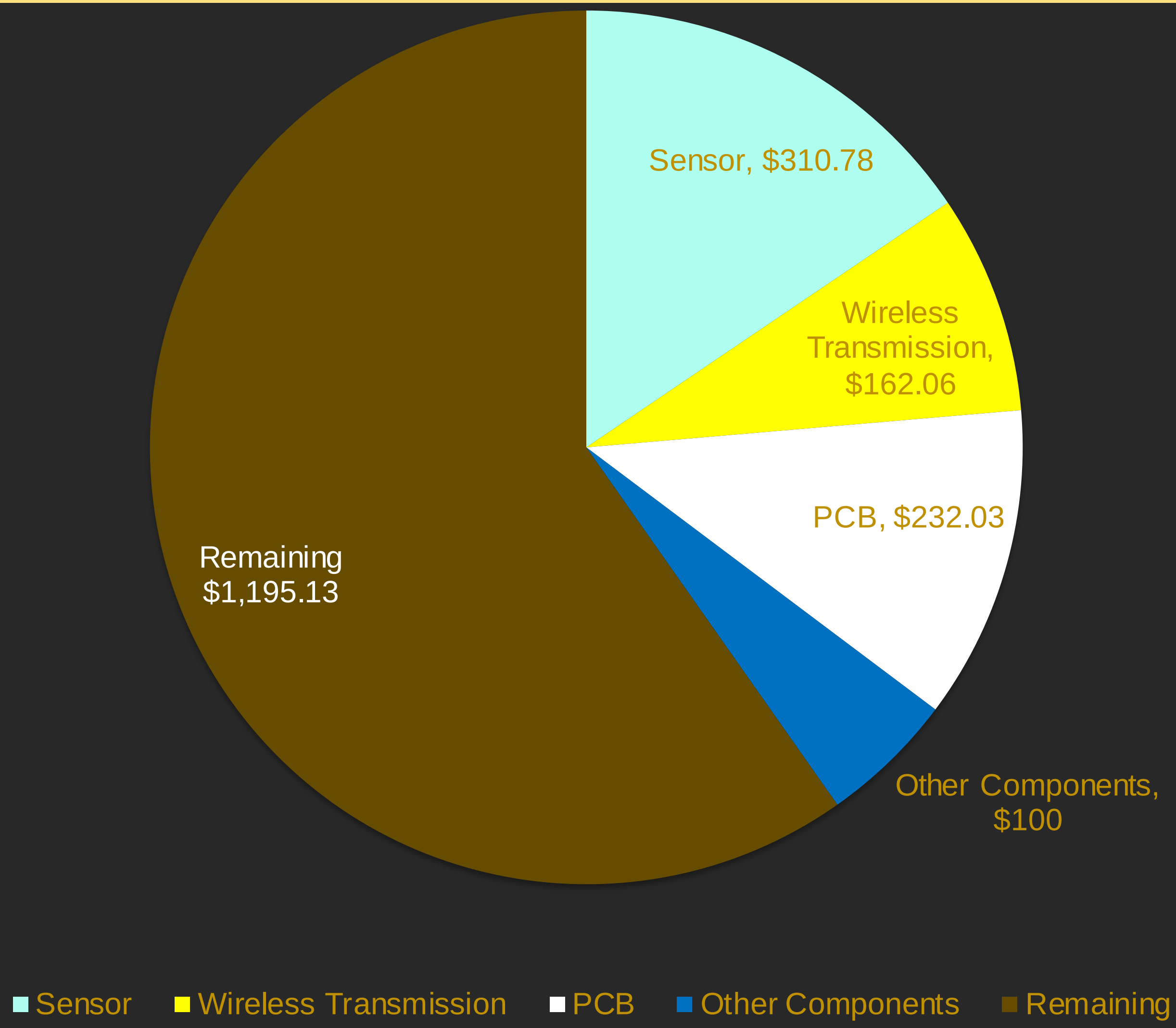
IMPROVEMENTS TO VERSION 2 AND 3 FOR MASS PRODUCTION

- Reducing PCB size by 5%
- Adding a second ground pin on the UART pins
- Replacing V2.0 voltage and current IC
- Adjust SMD components for mass production to lower cost.



BUDGET

Gross Budget:
$2000



CONCLUSION

All-In-One PV Sensor is complete

- Two functioning prototypes with different current-sensing ICs
- Fully functioning sensing circuitry and ADC conversions
- ESP32 on-board successfully connects & transmits to database

Further tests will continue with OUC as we pass the board to them

- Multi-sensor tests will occur to ensure the database can handle more than one sensor
- Stress-tests will allow OUC to understand the input limits of the sensor

Future revisions aim to improve the board in all aspects.

- The TLV341 can be replaced to reduce input offset
- The board can be equipped with voltage protection
- Code uploading circuitry can be embedded rather than UART

THANK YOU

Any Questions?