EMAE 355 Group 7 Project 2 Report: Temperature, Salinity, and pH Sensor Module Package for Algae Growing River for Biofuel Production

Will MacCormack   Owen Braun   Julian Town   Natalia Parla Rodriguez

March 30, 2024

1 Executive summary

The proposed sensor and communications module is suited for monitoring algae growth in central Texas. The device is meant to float along the river where the algae is grown for biofuel production. The module is powered by thermoelectric generator units, which are situated between two thin metallic plates. The upper surface is covered with a thin layer that greatly increases the solar irradiation retained. The module includes sensors for temperature, pH, and salinity to keep track of the health of the algae. Data is processed using a Raspberry Pi Pico and data is transmitted using a Lora Radio Module. The entire system at maximum power draw only requires 0.7 Watts, with the rest used being stored in a battery.

2 Problem statement

The goal of this project is to develop a sensor module package that utilizes a thermoelectric generator for agricultural applications. The sensor module must be constructed sensors chosen to perform in a specific location with a specific crop. It must also be able to store and transmit information. If location and power draw conditions necessitate it, a method of energy storage should also be included.

3 Background

Algae is relatively easy to grow, quite common, and quite resilient. So much so, that it is usually seen as a pest or invasive species in recreational bodies of water. The advent of fertilizer increased this problem further. The nitrogen and phosphorus runoff causes algae to bloom in massive numbers. This has been harnessed in recent years–Algae is often commercially grown for biofuel production. Algae is rich in oils that can be pressed out of the bulk and burned [1].

Despite Algae's ease of growth, controlled salinity, pH, and temperature ensure optimal growth rate. [2]. The optimal values for each parameter are outlined below in Table 1.

Parameter	**Value with Units**	**Notes —**
Temperature	35 °C	[3]
Salinity	30 ppt	parts per thousand, [4]
pH	7-9	[5]

Table 1: Optimal Algae Growing Nutrient

The location chosen was central Texas, roughly west of Austin. Austin was used to gauge climate parameters because of its proximity to the desired region. Algae is generally grown during summer, so the months between June and August, inclusive, were picked for their warm temperatures. Austin had near-optimal values for Solar Irradiance and Temperature. The average daily irradiance value in the area is seen below in Figure 3. Regions exist with higher irradiance values, but the terrain is much rougher and less spacious. This area also had an ideal temperature of 35 °C. [6] Also to note is the average wind speed in the area, which is 3 m/s [7]. Hourly Values for irradiation, ambient temperature, and wind speed, which were used in the analysis section, can be found below in Appendix A.

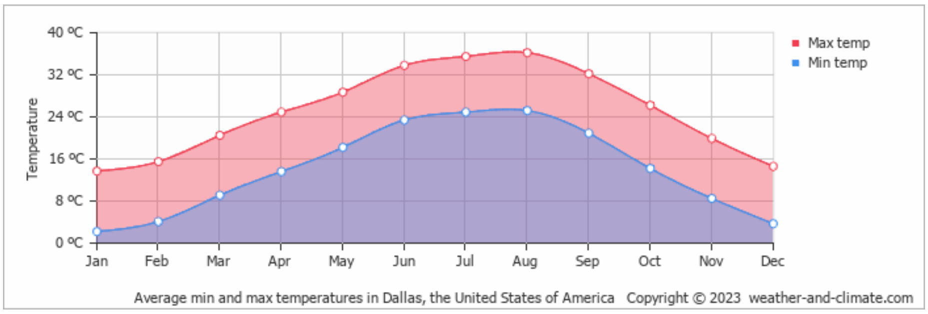

Figure 1: Temperature Graph each Month, Provided by [6]

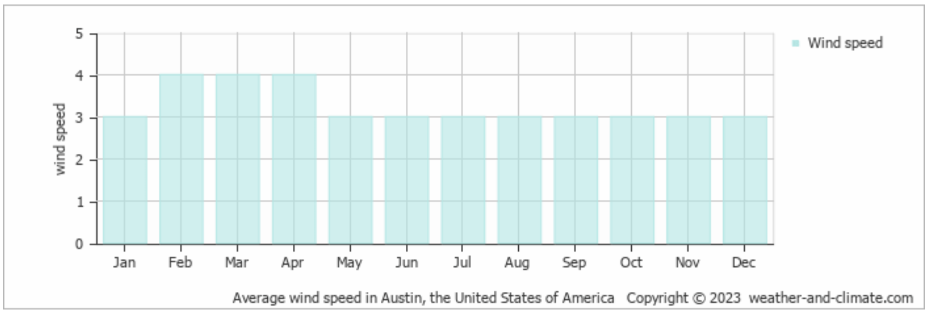

Figure 2: Wind Speed Graph each Month, Provided by [6]

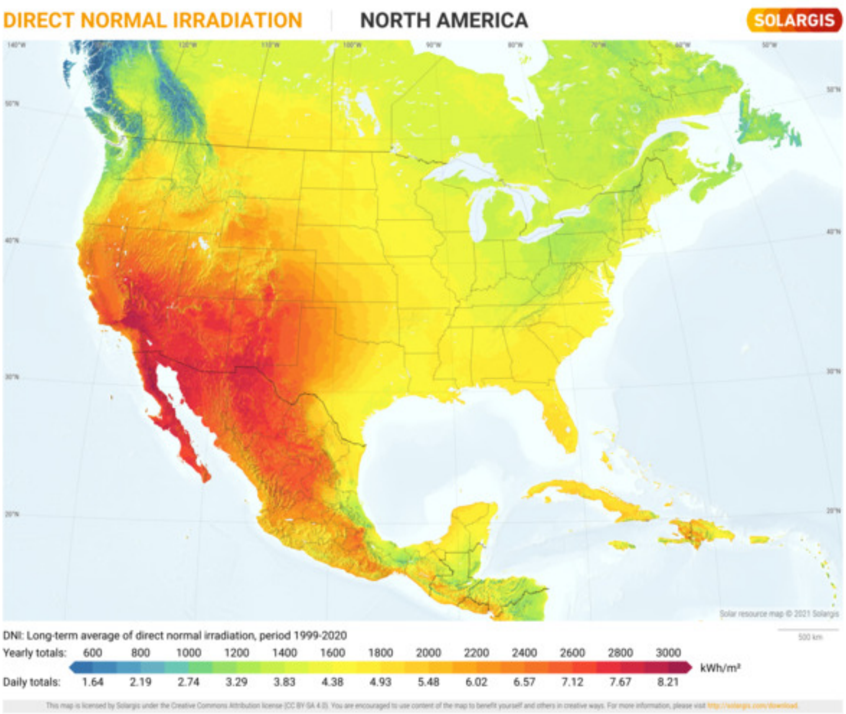

Figure 3: North America Solar Irradiation Map, Provided by [8]

4 Design – Lead: Julian Town

The entire module is sandwiched between two 5mm thick 1 meter square aluminum plates. Between the plates are the 15 thermoelectric modules, wired with three parallel groups of five modules in series to produce the required power output of 0.707 Amps at 3.3 Volts. The bottom plate acts to provide structure and to facilitate heat transfer by natural convection with the water. The top plate is covered with a thin layer of specialty material that enhances the energy retention through optimized radiation absorptivity and emissivity. Also between the plates are the batteries, control, and data transmission infrastructure. Surrounding the plate on all sides are flotation devices to keep the module floating. An onboard solar reflective array was rejected, as it would expand the footprint of the raft beyond reasonable operation in algae streams. Additionally, a ground based solar array would require prohibitively costly actuation and localization systems to direct solar radiation to a moving raft. The device was allowed to float with algae groups. Anchoring the system would defeat the algal cohort monitoring advantages of a floating platform, and would be better suited to a land-based, grid-connected station. The overall design can be seen below in Figure 4.

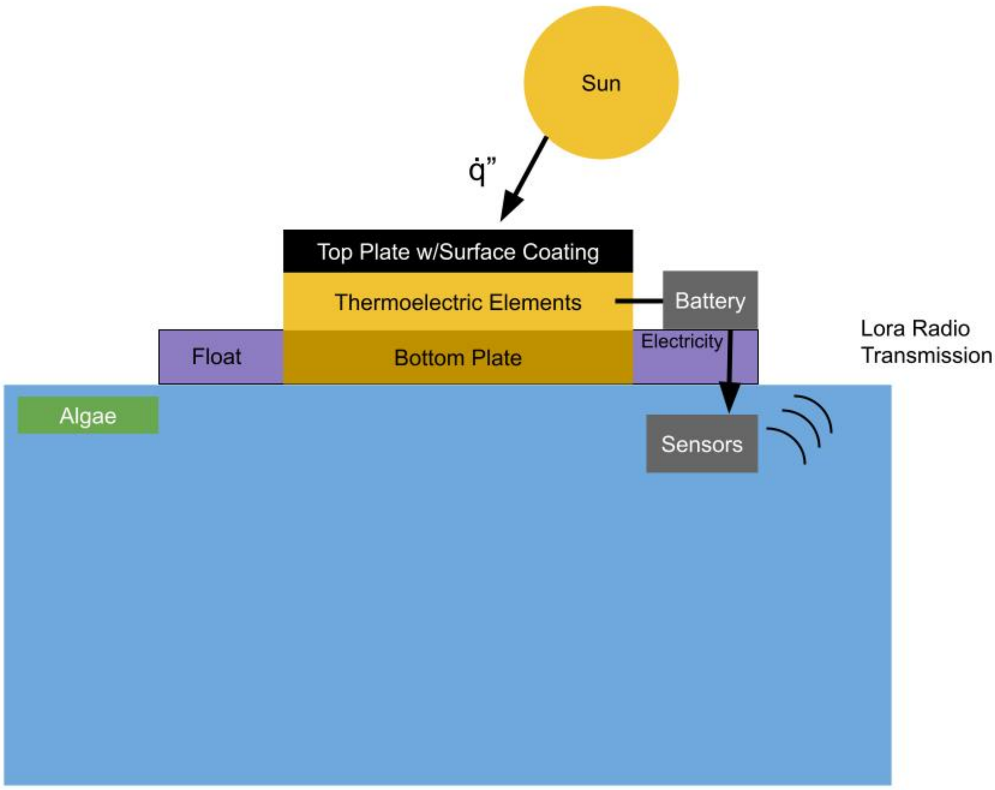

Figure 4: Overall Design

The coating on the top plate will be a specialty coating with a high absorptivity to emissivity ratio of 8 to 1 [9]. It is provided in strips 350mm long, which will be cut to the length of the plate. The thermoelectric generator will be a 1261G-7L31-04CL ThermoElectric Generator 30 x 30mm. Their electrical output as a function of hot and cold side temperatures are show in Figures 5 and 6. Excess power will be stored in a battery.

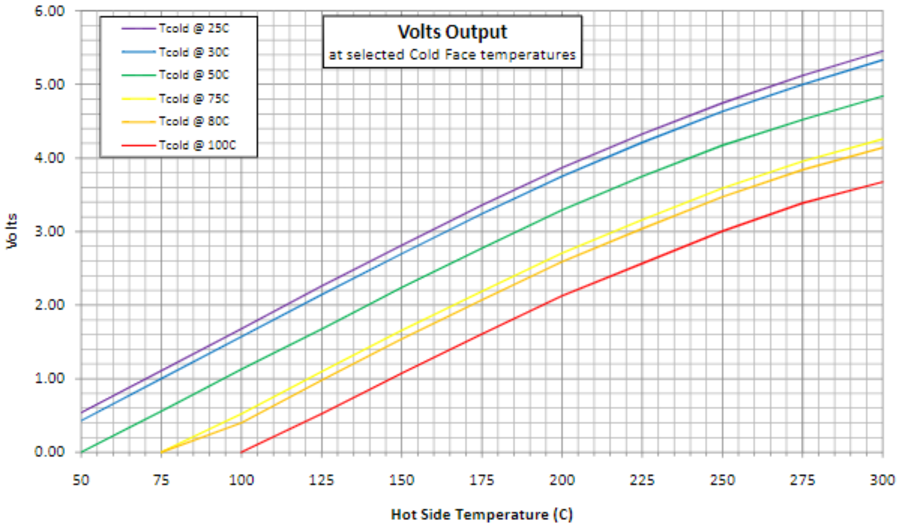

Figure 5: Voltage Output of TEG as function of Hot-side Temperature with for given Cold Side Temperatures. Provided by [9]

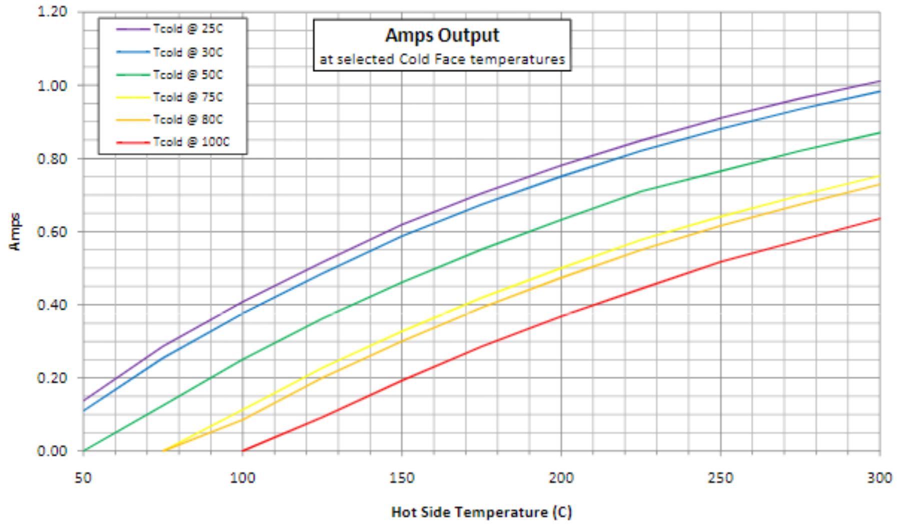

Figure 6: Current Output of TEG as function of Hot-side Temperature with for given Cold Side Temperatures. Provided by [9]

The data logging and other control features are handled by a Raspberry Pi Pico. This was chosen for its capabilities at such a low power draw: a mere 0.139 Watts (see Appendix D). The data transfer will be performed by a Lora Radio Module for 0.413 Watts.

To measure Salinity, the module will use a EZOEC Embedded Conductivity Circuit. This can measure a range of 042 parts per thousand (ppt) at an accuracy of 2%. It will be able to detect upwards of a 50% change in salinity given a target value of 30ppt. The sensor also has a low power draw at only 0.112 Watts. To measure pH, the module will use a EZOpH Embedded pH Circuit. The board has a range of 0.001 to 14.000 for pH, at a resolution of 0.001 and an accuracy of 0.002. Since algae is relatively hearty and grows from a pH range of 7-9, this sensor is sufficiently accurate. The pH sensor has a power draw of 0.044 Watts. Lastly, the temperature of the water will be measured using a thermistor.

The overall power draw while transferring data is 0.707 Watts. The majority of the time, the module will not be transferring data and only draws 0.294 Watts. The power draw for each component and totals at different states are summarized below in Table 4.

Component(s)	Power Draw (W)
Salinity Sensor	0.112
pH Sensor	0.044
Raspberry Pi Pico	0.139
Lora Radio Module	0.413
Data Collection Total	0.294
Data Collection & Transmission Total	0.707

Table 2: Power Draw Conditions

5 Analysis – Lead: Owen Braun

Thorough heat transfer analysis was conducted to ensure the temperature differential across the thermoelectric generator was sufficient to meet the power consumption needs. The data for ambient conditions (temperature, wind speed, and solar irradiation) on an hourly basis was sourced from the National Renewable Energy Laboratory. Data from June to August, inclusive, was used for the analysis and is found in Appendix A.

The heat transfer through the thin film due to conduction is not included in this analysis because thermal conductivity parameters were not provided. The thickness also maximizes at two tenths of a millimeter. This thickness will result in a very small change in temperature, so it is not significant enough to be included.

5.1 Top Plate Forced Convection

The top plate experiences forced convection due to wind. The data sourced provides hourly data, so the heat transfer is assumed to be the average over that hour. The convection coefficient can be calculated using the following equations. First, the Reynolds number is calculated.

$$Re = \frac{u_{\infty} * L_{plate}}{\nu} \quad (1)$$

Next, the Nusselt number can be calculated using the following equation if below the critical Reynolds number:

$$Nu_L = 0.453 Re_{L_{plate}}^{1/2} Pr^{1/3} \quad (2)$$

If Re_{plate} is above the critical Reynolds number of $5 * 10^5$ the following equation is used:

$$A = 0.037 Re_{crit}^{4/5} - 0.664 Re_{crit}^{1/2} \quad (3)$$

$$Nu_L = (0.037 Re^{4/5} - A) Pr^{1/3} \quad (4)$$

The convection coefficient (h_a) for the top plate can then be calculated:

$$h_a = \frac{Nu_L k_a}{L_{plate}} \tag{5}$$

The heat transfer rate can then be calculated below:

$$\dot{Q}_{conv} = h_a(T_{top} - T_\infty)A_{plate} \tag{6}$$

5.2 Top Plate Radiation

Additionally, the top plate absorbs and emits heat through radiation. The heat transfer rate due to radiation is shown below:

$$\dot{Q}_{rad} = (\alpha G - \epsilon\sigma T_{top}^4)A_{plate} \tag{7}$$

5.3 Bottom Plate Natural Convection

The bottom plate experiences natural convection as it is submerged in the algae pool. Since the float is not anchored, the relative velocity of the float with respect to the water is at worst zero. Thus, natural convection analysis is used instead of forced convection. First, the thermal coefficient of expansion of the fluid (β) is calculated:

$$\beta \approx -\frac{1}{\rho}\frac{\rho_\infty - \rho}{T_\infty - T} \tag{8}$$

where ρ is the density of water at the water/algae temp using the Kell Formulation:

$$\rho = \frac{(999.8395 + 16.94518t - 7.98704E^{-3}t^2 - 46.17046E^{-6}t^3 + 105.5630E^{-9}t^4 - 280.5425E^{-12}t^5)}{(1 + 16.89785E^{-3}t)} \tag{9}$$

where ρ is measured in kg/m^3 and t is the temperature in °C from 0 to 150 [11].
Next, the Rayleigh number can be calculated:

$$Ra_x = \frac{g\beta\Delta T x^3}{\nu\alpha} \tag{10}$$

The Nusselt number is then calculated:

$$Nu_L = 0.52 Pr Ra_L^{1/5} \tag{11}$$

Lastly, the convection coefficient (h_a) for the bottom plate can be calculated:

$$h_w = \frac{Nu_L k_w}{L_{sink}} \tag{12}$$

5.4 Through TEG Conduction

The thermoelectric generator produces a temperature difference across due to conduction. The heat transfer rate due to conduction is:

$$\dot{Q}_{cond} = \frac{N L_{TEG}^2 k_t \Delta T}{t_{TEG}} \tag{13}$$

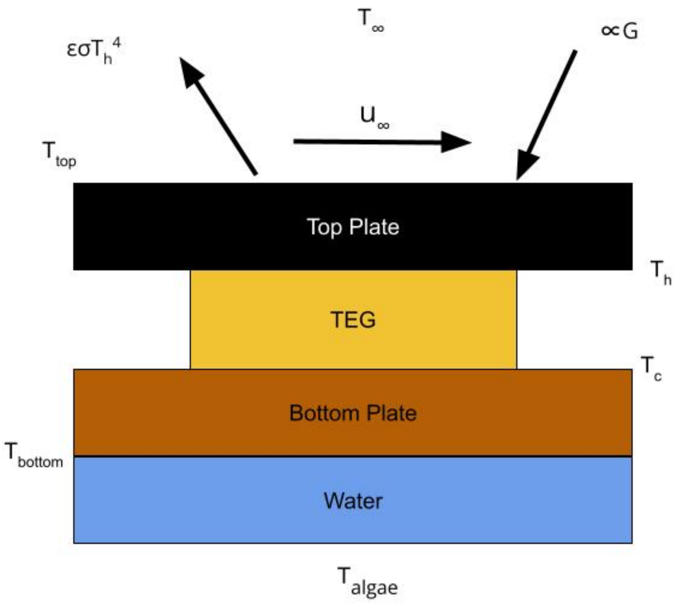

Figure 7: System Heat Balance

5.5 Through Plate Conduction

In order to model the conduction through the top and bottom plate between the external face and the TEG array surface, a linearly varying conductive side length with respect to thickness was employed. Solving for the constant area with an equivalent heat flux results in:

$$A_{eff} = \sqrt{N} L_{TEG} * L_{Plate} \tag{14}$$

This allows for a more accurate solution without prohibitively computationally expensive 3D conduction analysis. As the TEGs occupy a small fraction (1.35%) of the overall plate, it is assumed that the TEGs can be evenly spaced to ensure even heat distribution. Thus, the conduction heat transfer through the top and bottom plates is shown below:

$$\dot{Q}_{cond} = \frac{\Delta T k_{plate} A_{eff}}{t_{plate}} \tag{15}$$

where ΔT is T_{top} - T_h for the top plate and T_c -T_{bottom} for the bottom plate.

5.6 Heat Balance

Taking into account all forms of heat transfer, the overall thermal balance results in four equations. These two equations are solved simultaneously for the temperature of the hot side of the thermoelectric generator, T_h, and the cold side T_c. The heat balance equation for the top plate and the environment is shown below:

$$(\alpha G - h_a(T_{top} - T_\infty) - \epsilon\sigma T_{top}^4)L_{plate}^2 = \frac{(T_{top} - T_h) * A_{eff} * k_{plate}}{t_{plate}} \tag{16}$$

The heat balance equation is shown for the top plate and the TEG:

$$\frac{(T_{top} - T_h) * A_{eff} * k_{plate}}{t_{plate}} = NL_{TEG}^2 k_t t_t (T_h - T_c) \tag{17}$$

The heat balance equation is shown for the bottom plate and the TEG:

$$NL_{TEG}^2 k_t t_t (T_h - T_c) = \frac{(T_c - T_{bottom}) * A_{eff} * k_{plate}}{t_{plate}} \tag{18}$$

The heat balance equation is shown below for the bottom plate and the water:

$$\frac{(T_c - T_{bottom}) * A_{eff} * k_{plate}}{t_{plate}} = h_w(T_{bottom} - T_{algae})L_{sink}^2 \tag{19}$$

The constant parameters used in these equations include absorptivity, α, the emissivity, ϵ, the Stefan-Boltzmann constant,σ, the lengths of items, thermal resistances of materials, and thicknesses. The values of these parameters are summarized below in Table 3.

Parameter	**Value (Units)**
Pr_{water}	6.9
Pr_{air}	0.71
k_{water}	0.6 W/(mk)
k_{air}	0.0259 W/(mK)
k_{TEG}	1.72 W/(mK)
k_{plate}	237 W/(mK)
Absorptivity	0.96
Emissivity	0.12
t_{plate}	5 mm
t_{TEG}	3.75 mm
t_{sink}	5 mm
L_{plate}	1 m
L_{TEG}	30 mm
L_{sink}	1 m
T_{algae}	35 ° C

Table 3: Constants and Parameters for Thermal Analysis

5.7 Solving methodology

The system performance was analyzed across three months of hourly data from the National Renewable Energy Laboratory [correct this name if it is wrong]. Each hour of conditions was solved identically, and then the 2208 hours of performance were viewed together to understand the annual performance of the system

5.7.1 Hourly Solving Methodology

Ambient temperature, solar irradiance, and average wind speed were provided for any particular hour by the hourly ambient conditions data. Ambient temperature was used as the T_∞ for the top

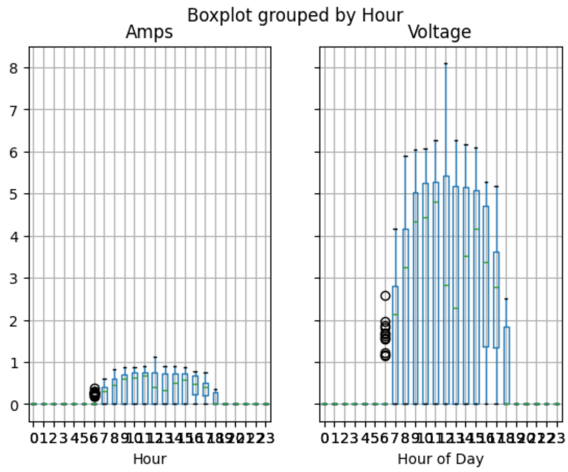

Figure 8: Electrical Output vs Hour of Day

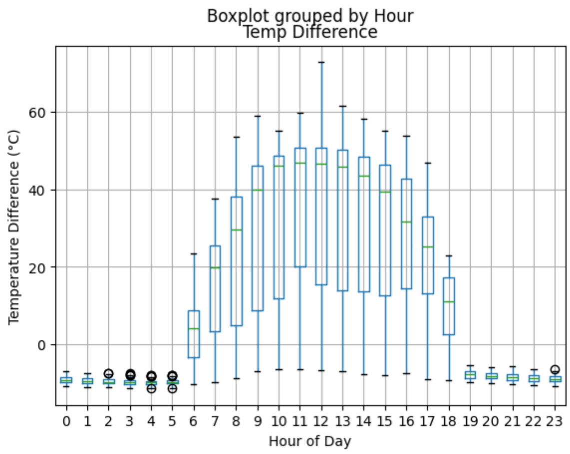

Figure 9: Temperature Difference vs Hour of Day

side forced convection analysis. Likewise, the average wind speed was used as the u_∞. Lastly, the solar irradiance specified the incident radiation flux for the top surface radiation balance. All other parameters were treated as constant across all hours and are specified in Table 3.

With all parameters specified, the system of heat transfer balances was entered into SciPy and solved numerically due to the non linearity in the Radiation and Free Convection terms. Once surface temperatures were returned by the numerical solver, the voltage and amperage production of a TEG module was calculated through a SciPy two dimensional interpolation of the manufacturer provided performance data. Per module electrical outputs were then converted to overall electrical performance by multiplying voltage by modules in series and current by modules in parallel.

5.7.2 Battery Sizing Analysis

A battery for the system was sized based upon the principle of energy redistribution. The net power production of the system–gross power less the maximum power draw of the sensor platform–was analyzed to find the smallest window of hours that would guarantee a non-negative sum of

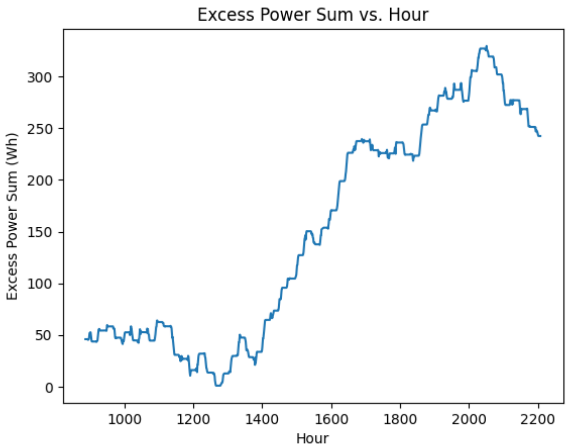

Figure 10: Net Power Sum at Smallest Non-Negative Window

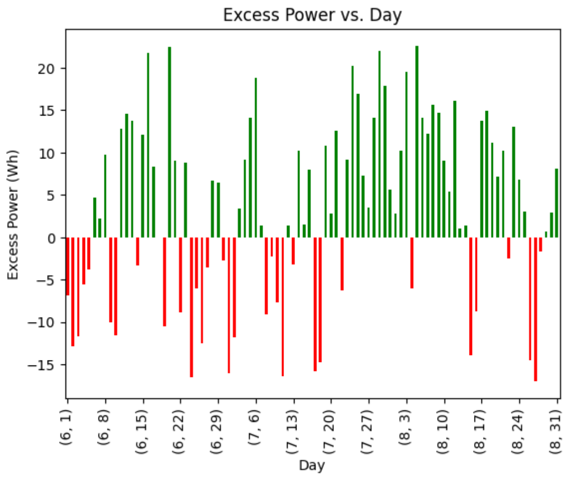

Figure 11: Net Power Production vs Day

net power. This was achieved through the Pandas rolling sum functionality. This hourly battery requirement was then multiplied by the maximum power requirement of the sensor platform to compute the total required battery size.

Metric	Value
Maximum Power Production (W)	9.115
Maximum Hot Side Temperature (°C)	113.3
Average Power Production (W)	0.8459
Total Watt Hours Captured (Wh)	1867.8
Annual Operation (hours)	2208
Battery Requirement (Wh)	627.98

Table 4: Overall System Metrics

6 Evaluation

The module has many benefits. Firstly, it is incredibly simple. The entire apparatus fits onto a single plate. It is easy to transport for shipping and installation. The design consists of a few commercially available sensors, boards, and coatings. Additionally, the module is self sufficient. Once placed in the desired stream, it will float around the entire algal system. It does not need any fixed connections for power or data, only a LoRa repeater within 10km. The wireless data transmission allows for constant monitoring without the need for onsite personnel.

The biggest benefit of this module is its low power draw and high reliability. The entire module, at maximum energy expenditure, is only 0.707 Watts. Moreover, The system has been validated across the wide variety of thermal, wind, and solar conditions present during growing season, not just monthly averages. The module's low power draw coupled with a battery sized by hourly analysis not empty promises ensures this system will be the last module running come wind, rain, or frost.

7 References

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