Exploring the Feasibility of Concentrated Solar Power for Use with Peltier Devices to Generate Electricity

[redacted]

Activity Report

Abstract—Traditional solar panels will only generate electricity during the day. This device will lay the groundwork for exploring the potential of using the sun's heat to charge and power a device that will generate electricity during the day and night. This would allow greater flexibility with fluctuating load demands, consistency, and decrease the need for energy storage, which is the current solution. Furthermore, we hope to investigate the possibility of merging this technology with current PV cells to create a hybrid solution.

Index Terms—CSP - Concentrated Solar Power , PV - Photovoltiac

1 Impact

CONCENTRATED Solar Power focuses on harnessing the heat from sunlight to generate electricity. In almost all cases, this is done to create steam, and then use it as any traditional generator would. In our application, we propose instead utilizing a device called a "Peltier". These are small, solid state devices that, when provided a temperature difference between its sides, will generate electricity. In this regard, we hope to capitalise upon the temperature difference between day and night, although it will still operate during the day. If water, or some equivalent liquid, could be heated effectively during the day, and then stored in an insulated environment for night, a significant temperature difference could be obtained, creating optimal operating conditions for a Peltier. In theory, if the stored heat decreased slower than the outside temperature, the device would actually perform better during the night. This project would provide a new approach to CSP, and be completely environmentally friendly. This type of generator could easily be deployed anywhere in the world, and help provide electricity to those in need. Similar to traditional PV cells, this could also be installed on the ceilings of buildings, making it impactful in urban areas, as well as the rural and remote.

2 Related Work & Market Research

In almost all work with CSP, the heat from the sun is used to power an engine or turbine that is connected to an electricity generator. [1] Unlike our proposed device, which would theoretically operate better at night, these do not work at all then, unless they incorporate Thermal Energy Storage or Backup Systems. [2] However, even within traditional CSP, there are several different methods for harnessing the heat from the sun.

2.1 The use of Parabolic Trough Collectors

By far the most mature technology, parabolic troughs have been implemented in many different CSP plants and proven themselves in the field. In 2004, they had an electrical efficiency of roughly 10-15 percent. [3] They simply involve a parabolic, reflective surface that concentrates the suns heat into a pipe containing a working fluid, that is then heated as a result. This fluid, usually molten salt, is then pumped to create steam.

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The use of Fresnel lenses

Very similar to Parabolic troughs, Fresnel systems use mirrors to reflect the suns heat unto a parallel absorber, which carried a working fluid that heats water. However, unlike most Parabolic troughs, Fresnel lenses generally use a tracking device that follows the sun to ensure maximum thermal energy. This is very similar to the technology used in PV cells. [1]

3 Ethics

The largest legal consideration to take place, if this device were to be scaled to an industrial level, would be to make sure that the receiver pipe is adequately protected and built properly to ensure no safety concerns arise. On a larger scale, this pipe will get incredibly hot, and could prove to be hazardous if broken. Additionally, the reflected heat from the parabolic trough is also very strong. As such, adequate measures will need to be taken to ensure the beam is always directed at the receiver pipe.

4 System Requirements

Since this project requires the use of two key types of technologies, those being Peltier devices and parabolic troughs, the user stories and subsequently the system requirements for this sprint revolve around them. In order to properly build our device, we need to first determine exactly how much power can be extracted from a Peltier under a variety of induced conditions. Furthermore, we needed to determine the amount of heat that can be focused from a modestly sized parabolic trough, and the dimensions required for such.

4.1 Peltier Device Testing

”As a Student working on this project, I need to spend adequate time researching and testing the efficiency of Peltier devices before building to ensure that we have the correct number in our array to get the proper output power we desire.”

4.1.1 Functionality

Before even focusing on the use of CSP with Peltier devices, we first needed to determine the amount of power a single device can produce, under certain conditions. Specifically, to test the power at different heat differences and to test the amount of cooling needed for effective operation. These tests will be conducted by connecting multiple Peltier devices to a heat-conductive material, presenting a temperature difference, and measuring the output. A basic cooling system will be implemented with a single fan and aluminum heatsink, and tested on its ability to maintain the desired temperature difference.

4.1.2 Acceptance Criteria

The acceptance criteria will be met when when final test data with accurate estimates of what each Peltier can produce at different temperature differences, and the effectiveness of cooling is acquired.

4.2 Parabolic Trough Research

”As a Student working on this project, I need to spend adequate time researching the technology behind Parabolic troughs as well as build a CAD model Trough to ensure we build it properly when construction begins.”

4.2.1 Functionality

In order to accomplish this user story, we will begin by researching parabolic trough technology. This research will encompass both the effectiveness and heat focusing potential, in addition to physical construction materials. Then, we will create a CAD model of this trough, following the specifications determined by our research.

4.2.2 Acceptance Criteria

The acceptance criteria for this user story will be met once we have a generic dimensions for a parabolic trough and have a completed CAD model for it.

4.3 Parabolic Trough Design

“As an operator of this device, I need a Parabolic Trough to focus and focus the suns’ heat to generate electricity.”

4.3.1 Functionality

In order to accomplish this user story, the final dimensions for our parabolic trough must be determined. They must be backed up with science and defined by exact formulae. After this, a physical Parabolic Trough must be built from cheap materials and tested.

4.3.2 Acceptance Criteria

The acceptance criteria for this user story will be met once we have exact dimensions for our parabolic trough and a physical prototype built to those dimensions.

4.4 Constraints

Our constraints and requirements for this project were fairly open ended. Even so, it was very important to our stakeholder that we create physical tests and prototypes, and not just CAD models. As such, this is one of the reasons that we will build an real world environment to test our Peltier devices, and will not be relying on data sheets. This will eventually lead to us creating a Minimum Viable Product version of our device, physically built by the end of this semester. Cost is always a driving factor as well, and we must strive to so everything as cheaply as possible.

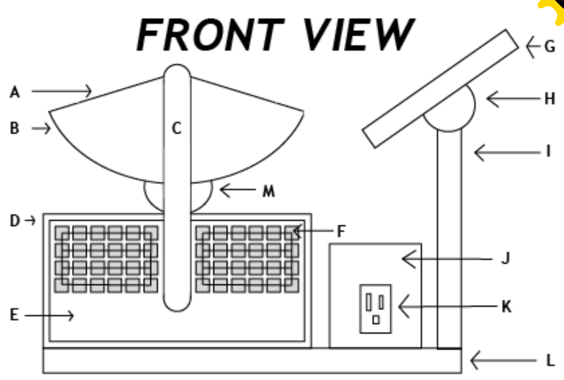

Figure 1. System Architecture Diagram

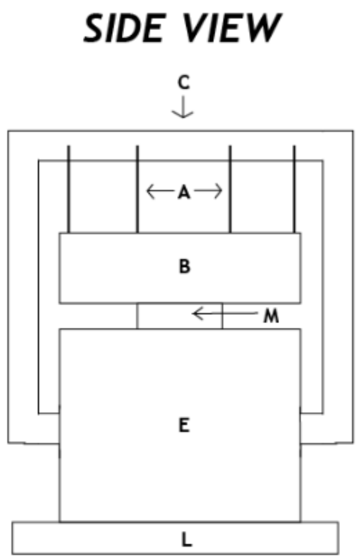

Figure 2. System Architecture Diagram

5 System Design

5.1 System Architecture

Notated in Figures 1 and 2, (A) - Support Rods. These will hold the parabolic trough in place. (B) - Parabolic Trough. A curved, reflecting mirror surface. (C) - Absorber tube. Contains a working fluid that is heated by the reflected heat, Runs through the water tanks to store the heat. (D) - Insulation for the water tank. (E) - Water tank and pump system. (F) - Peltier Array. Uses the temperature difference between the inside of the water tank and the outside air to generate electricity. (G) - Solar Panel. Tracks the sun during the day to best generate electricity. (H) - Gearing system. Rotates the solar panel. (I) - Solar Panel base. (J) - Battery and Electronics HQ. Stores the excess energy and controls the entire device. (K) - Electrical output. (L) - Foundation. (M) - Gearing System to rotate the Parabolic Trough.

The images displayed are our best interpretation of what our final device may look like. Heat will be reflected by the Parabolic Trough (B), into the Absorber tube (C). The fluid inside this pipe is then transferred inside of (E), where it will heat water that will then be used to fuel the Peltier Array (F). The use of PV cells here is also demonstrated, to be possibly used in conjunction to provide maximum power.

5.2 System Components

While our device holds the potential for a multitude of additional components, mainly for optimization purposes, the basic operation

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can be simplified into four main sections: The Parabolic Trough, Receiver Pipe, Pump System, and Peltier Array.

5.2.1 Parabolic Trough

The Parabolic Trough is responsible for reflecting and focusing heat from the sun unto our receiver pipe. When taking a cross-section of this reflector, it can be described with the formula of

$$y = \frac{1}{4f}x^2$$

with 'f' being the focal length and 'y' being the path of the parabola's cross-section. This was inspired from an article on Parabolic Trough technology. [4] In most industrial applications, $f = 1.75m$, however, to keep our prototype small, ours was scaled down to $f = 0.175m$, with an Aperture Width, the distance between the opposite tips of the parabola, of $a = 0.6m$, and a length of $l = 1m$. See figure 3.

5.2.2 Receiver Pipe

The Receiver Pipe, located at the Parabolic Trough's focal point, collects the reflected heat and stores it in water. This pipe is generally made of a material such as copper, but our design instead utilized a painted PVC pipe due to budget concerns. The minimum diameter of this pipe can be determined from the formula

$$D = \frac{l sin(0.267)}{sin\phi}$$

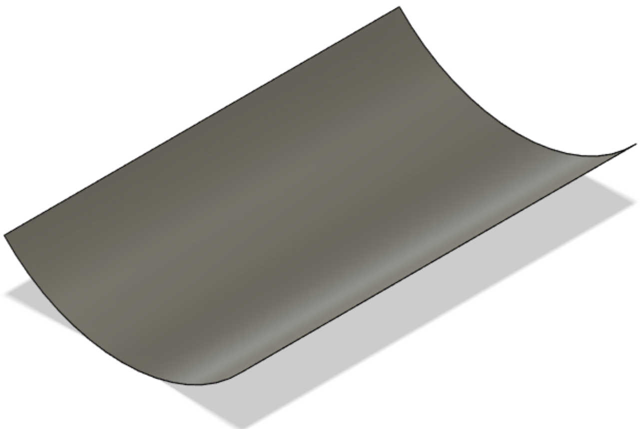

Figure 3. CAD Model of Parabolic Trough

where $\phi = arctan(\frac{0.3}{0.0464}) = 81.2$, the angle between the focal point and the tip of the Parabolic Trough, and $l = 0.6m$. This comes to a minimum pipe diameter of 30 mm. When determining phi, 0.3 is the distance from the midpoint of the parabola to either tip, and 0.0464 is the distance from the receiver pipe to this midpoint. When plugged into arctan, this yields the angle between the focal point and the tip of the Parabolic Trough. [5]

5.2.3 Pump System

The Pump System is responsible for circulating the water, and subsequently the heat, from the Receiver Pipe to an insulated storage tank for use with the Peltier Array.

5.2.4 Peltier Array

The Peltier Array is a large connection of Peltier devices. They will be utilizing the heat difference between the storage tank and the outside air to generate electricity. Future tests and analyses must still be completed, but as of our current research, a single Peltier is capable of producing a mimimum of 100mW of power when presented a 120 degree Fahrenheit difference.

5.3 Engineering Standards

The main engineering standards that we have adhered to, so far, are specific to part sizing.

5.3.1 Parabolic Trough Dimensions

The formula mentioned in section 1.2.1 is a common standard in CSP plants. We simply adapted the proven formula to a size more workable for our project.

5.3.2 Receiver Pipe Diameter

The formula used in section 1.2.2 for determining the minimum receiver pipe diameter was critical to ensure that we had a pipe that was large enough to receive all of the reflected heat from the Parabolic Trough. Commercial CSP plants also have Receiver Pipes that must follow this rule.

EXPERIMENTAL DESIGN

6.1 Design

There were four distinct tests conducted this semester. Listed below, they are:

6.1.1 Temperature Limits

These tests were considered a success if they determined a max-capacity temperature for our receiver pipe and also determined an estimate of the heating power of our parabolic trough. The subsequent hypothesis for this, in accordance with what we defined as successful and from the previous iteration of these tests, was that the maximum temperature for the pipe would be 104F and that the heating power would be 33 Watts. The independent variables were the distance that the lamp was from the pipe, and whether or not there was a parabolic trough. The dependent variables were the temperature of the water, the time that the test was run, which in this case was as long as it took for the temperature to level off, as well as the environment that the tests were run in. We controlled for bias by replicating the previous iterations of these tests as closely as possible and comparing data from those previous tests.

6.1.2 Outdoor Parabolic Trough Testing

In this group of testing we decided to change the environment of testing to outdoor conditions. This test would be considered successful if we are able to prove that the trough can function in a setting where the sun is the main source of heat. The hypothesis we are testing is that the trough will concentrate enough solar energy to heat the water within the receiver pipe. The independent variables were using the sun as a heat source and also location of the trough outdoors. The dependant variable was the heating power of the trough system.

6.1.3 Peltier Power Production

This test was considered a success if it determined a relationship between the power from a single Peltier device and the temperature difference imposed across it. Our hypothesis was that as the temperature difference decreases, the power from the Peltier will decrease exponentially. The independent variable was the temperature of the water reservoir. The dependent variable was the voltage across the measured ten Ohm resistor. We attempted to control for bias by taking voltage measurements as frequently as possible.

6.1.4 Peltier Power Scalability

This test was considered a success if it determined an estimate for the scalability of our Peltier devices. Our hypothesis was that as you increase the number of peltiers in the system, the amount of power produced by the system will show a direct relationship and also increase at a constant rate. The independent variable in this experiment was the number of peltiers linked in series, which we changed between every data point collection. The dependent variable was the power produced by the system and this was recorded by measuring the voltage across a known resistance.

6.2 Results

6.2.1 Temperature Limits

When looking to the heat generation and subsequent energy production of the parabolic trough, it was found that a consistent temperature difference would be needed to maintain the power output that was desired. To test for this, two experiments were conducted, the first of them, henceforth called ”control test”, involved the use of a pipe and a lamp that was placed a foot away from it. This test was used to determine the heat capacity of the pipe by measuring how long it took the water in the pipe to be heated to a stable temperature. Similar to this, the other test, henceforth called ”trough test”, replicated this exact setup, but with the addition of the parabolic trough. Both tests were recorded and the results can be seen in Figure 4.

The two tests were run for approximately 8 hours, with the control test leveling out at 104F and the trough test leveling out at 108F. In addition to this, it should be noted that the linear regions of these graphs where the temperature initially rose from its original temperature to the one it leveled off at was significantly smaller for the trough test versus the control test. With the control test taking 5 hours giving

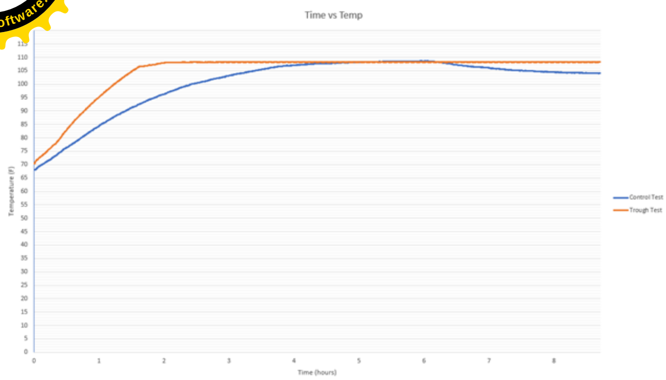

Figure 4. Temperature Limit Test Results

it a linear fit of $y = 0.0375x + 75.849$ and the trough taking 1 and a half hours, giving it a linear fit of $y = 0.092x + 72.808$. These can both be seen in Figure 5, where the specific linear growth regions have been isolated.

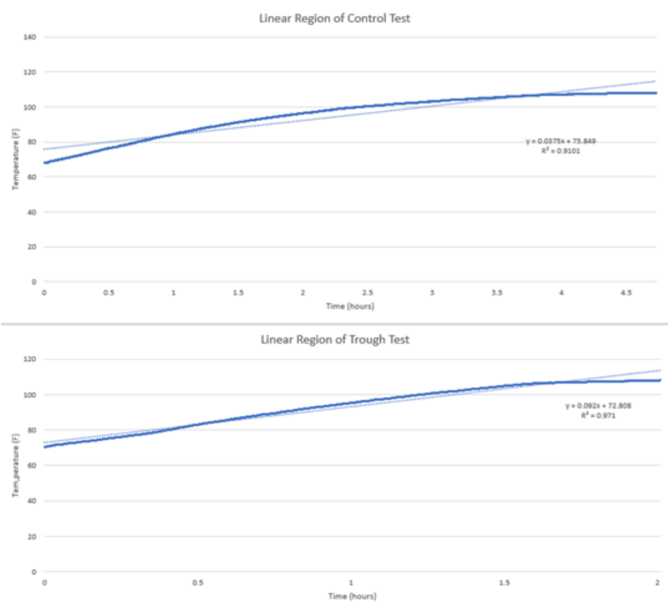

Figure 5. Linear Regions

6.2.2 *Outdoor Parabolic Trough Testing*

The first outdoor test, conducted using our Parabolic Trough with a cardboard backing shown in figure 6, was able to reach a maximum temperature of 108 F after 75 minutes. The other outdoor test, conducted using our Parabolic Trough constructed from Lattice shown in figure 7, was able to reach its maximum temperature of 101 F after 50 minutes

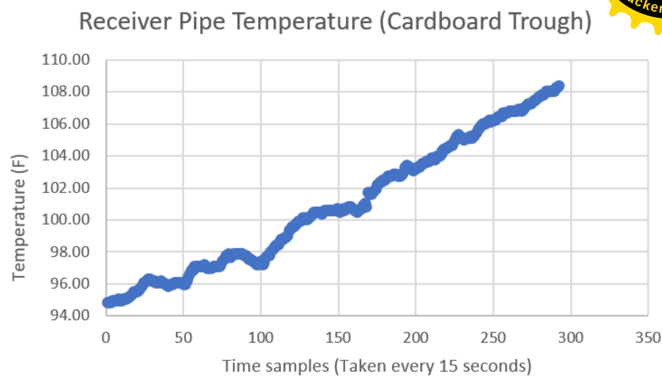

Figure 6. Outdoor Cardboard Reflector

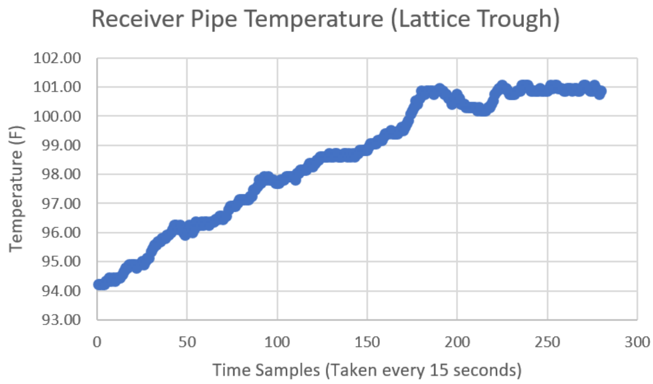

Figure 7. Outdoor Lattice Reflector

6.2.3 *Peltier Power Production*

For this test, a simple testing environment was utilized, shown in figure 8.

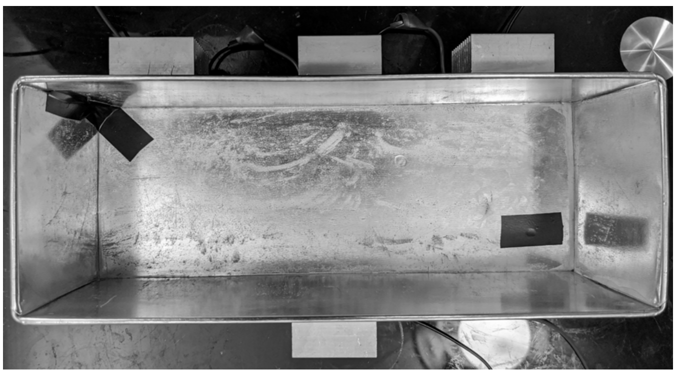

Figure 8. Original Peltier Testing Environment

The environment contained a metal reservoir for hot water, three Peliter devices in series on one side, and a single Peltier on the side opposite of that. To start the test, water was heated to 200 F and poured into the reservoir.

At that point, the power outputs of both Peltier systems were recorded in the form of voltage across a 10 Ohm resistor, shown is figure 10. The temperature of the external heatsinks and the water in the system was also recorded, and is shown in figure 9.

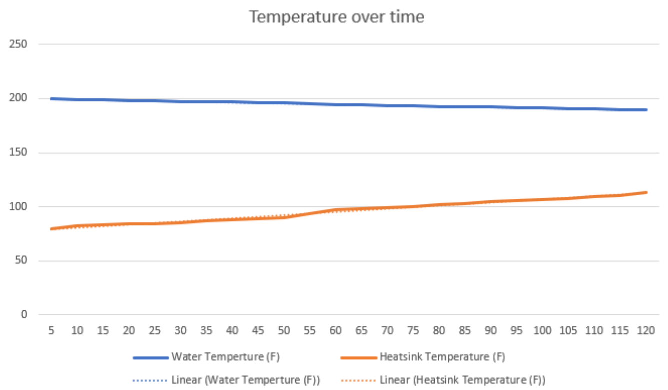

Figure 9. Water Temperatures

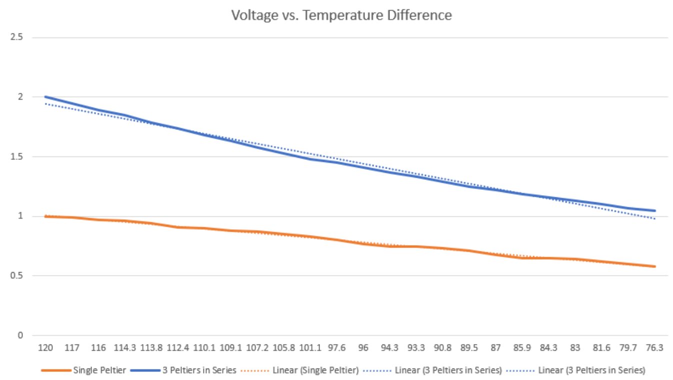

Figure 10. Voltage Across a 10 Ohm resistor

6.2.4 *Peltier Power Scalability*

An important test we ran was to explore the scalability of peltiers in our system. We set up a test with as many as 8 peltiers together to see if the power produced would follow a trend. The test would follow the procedure used in previous trials where we bring water to a boil and pour it into the testing environment to create a temperature difference. We connected the peltier devices in series and measured the voltage across a 10 ohm resistor. With the voltage and resistance values, we are then able to calculate the amount of power produced. The data produced shows an exponential increase in power production from one to six peltiers, but afterwards we notice a slight drop-off in power. In order to obtain a reasonable exponential best fit line, we may omit the last 2 data points in the chart. As you see in equation 1, this gives us an exponential fit of

$$y = 0.6497e^{0.6719x} \tag{1}$$

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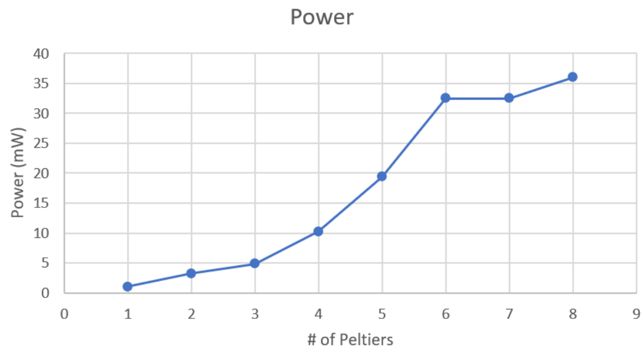

Figure 11. Peltier Power Scalability Test Data

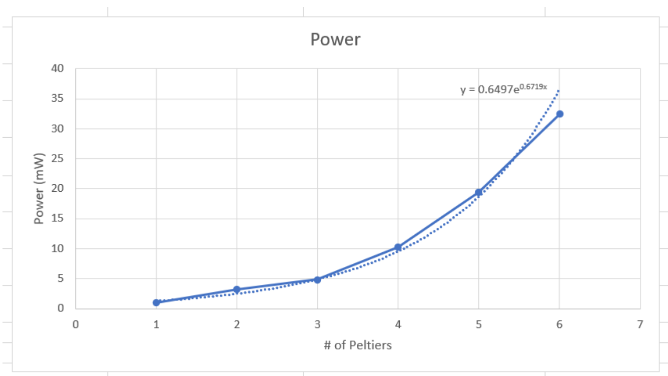

Figure 12. Scalability exponential fit

7 Discussion

7.1 Temperature Limits

The results in Figure 4 and 5 show a few key takeaways, the first being that the pipe with the trough was capable of heating to a stable temperature at a much faster rate than the pipe just being heated by the sun, or in this case, the lamp. Additionally, the temperature reached on the test with the trough was slightly higher than that of the control test, which could be attributed to an additional part of the pipe being heated because of the reflective surface of the trough.

Given this data, the heating power of each of the setups was also able to be found. This was done through the use of the following equation

$$\frac{(Weight) * (TFinal - TAmbient)}{(HeatingTime)} \tag{2}$$

The resulting heating power of the control test was 19.47 Watts, while the heating power of the trough test was 30.2 Watts. These results ended up falling in line with the previous iterations of these tests, with the percent difference between the previous trough test and the one done during this sprint being 11.3%.

These results not only validate the results of the previous tests, but give us an optimal laboratory scenario with which real world tests on the trough can be compared to; branding this phase of testing as successful insofar as it has confirmed the results of previous test.

7.2 Peltier Power Production

One of the key takeaways from this test was the relationship between a temperature difference and the power produced by a single Peltier, found to be

$$\frac{(-0.00961(120 - \Delta T) + 1.03)^2}{10} = P \tag{3}$$

This took the assumption that future data would follow the results collected during our tests. Assuming this information is correct, this information will be useful when determining the power capabilities of an array of Peltiers. However, to properly determine this, we still needed to know how well the power scaled with each additional Peltier.

7.3 Outdoor Parabolic Trough Testing

This test shows that the lattice structure is an optimal choice for the solar reflector, as it can reach a far greater temperature then cardboard, especially in outdoor conditions. This is also valuable for our design as the lattice is waterproof, whereas the cardboard system is not. Overall, it was clear that the Parabolic Trough was having a noticeable effect on the heating as the temperature in the receiver pipe was able to steadily grow. This proves that our system has the potential to be viable outdoors, just like we had hoped in our hypothesis.

7.4 Peltier Power Scalability

When we look at our exponential line of fit given from 12, this gives us a formula that can be used to find the power depending on the number of peltiers in the system. This can be used to predict the amount of power produced by any number of peltier devices by plugging in a value for X. However, this data cannot be compared to the expected values we calculated by using a single Peltier because the testing environments did not share an equivalent temperature difference.

7.5 Limitations & Future Work

The experiments run during this and the prior sprints encountered a variety of issues, while some had workarounds, there are definitely improvements that can be made, some of which are highlighted below:

- **Recommendation 1:** The trough apparatus suffered from structural issues, specifically in that the supporting wood was incapable of supporting the lattice-backed trough without breaking. This problem could be fixed by designing an apparatus that is modular and can be modified on the spot to adhere to an variables in the trough or environment.
- **Recommendation 2:** A major limiting factor to our new peltier array is the inability to track the temperature on both sides of all peltiers in real time. This can be a huge problem, as knowing the exact temperature difference is critical to our work. This could be solved by including dedicated temperature sensors on either side of the testing environment and tracking their inputs with an arduino.
- **Recommendation 3:** A recommendation we would put forward for the scalability experiment would be to find an easier way to add or remove Peltier devices from the system in a much quicker way. This would allow less time for the temperature

to lower and therefore give unexpected data outputs.

8 Conclusion

Our goal was to create a system that reliably generated renewable energy using Concentrated Solar Power with Peltier devices. While we have not yet achieved this goal, we have made great progress. Now that we have an idea of the true heating power of our trough, a much better one can be logically designed with the entire system in mind. Now that we have an estimate of the power capabilities a single Peltier can produce and a scaling relationship, a proper Peliter array can now be designed and integrated. These accomplishments will pave the way for a complete working system, eventually leading to our desired goal.

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