Harvesting Energy from Tree Trunks

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ABSTRACT: **With the coming advent of smart devices, remote monitoring and long-range radio communication, there has been an increasing interest in alternative power sources and energy harvesting techniques to prolong indefinitely the smart devices life. One of these alternatives is to take advantage of the Seebeck effect, a natural occurring phenomenon by which the temperature difference between two different types of conductive materials produces a slight voltage difference between them. By leveraging the thermal difference between the core and the surface of a tree trunk there may be enough energy to power IoT devices. This paper discusses the design of a thermoelectric generator (TEG) based energy-harvesting module designed to power IoT Sensor networks that uses Xbee/Zigbee RF modules for communication. It shows how the energy harvesting devices are implemented in the field, as well as the discrete components designed for harvesting energy from a tree. It also shows the proposed solution for future experiments.**

Keywords: Energy Harvesting, Tree Trunks, Peltier Cell, Seebeck Effect, IoT.

1. Introduction

Modern Wireless Sensor Networks (WSNs) and the Internet of Things (IoT) provide data and analytics for safety, efficiency, and other means of monitoring. Analysts [1] suggest that there will be as many as 30 billion connected devices by 2020. These devices require a wide range of voltages to operate and are typically powered by conventional means such as municipal power, batteries, or renewable sources, such as solar arrays. Devices must also be connected to a host device which handles the data storage and communication protocols. These host devices require a significantly higher power than the sensors. The voltage requirement of the host devices is generally between 3.3 volts and 5 volts.

With 30 billion devices in the field, there are two factors that must be kept in mind: waste and accessibility. While many devices will be powered by municipal power, many remote devices are powered by disposable batteries, which create significant waste. While rechargeable batteries may seem like an appropriate solution, the accessibility and number of devices must be considered (for example, a network of sensors in a tree canopy would require significant upkeep, were it powered by rechargeable batteries.). It has been shown [2] that an Energy Harvesting system that powers the module by converting ambient energy into electrical energy would minimize waste and potentially remove the need for regular human upkeep on the modules.

The purpose of this study is to develop and test the viability of an energy harvesting system that uses Thermoelectric Generators (TEGs) to convert the naturally occurring thermal gradient between the core of a tree trunk and ambient air into usable electrical power. According to the work done by Protásio [3], it is possible to extract energy from tree trunks using the Seebeck effect.

This paper details the implementation and results of two experiments conducted between July 2nd, 2019 and August 13th, 2019. In both experiments, a 190mm Aluminum Rod was driven into the trunk of a healthy ponderosa pine such that the rod was completely embedded in the tree and the end of the rod was flush with the bark on the exterior of the tree trunk. A TEG was fixed to the end of the rod. The voltage across the terminals of the TEG was measured periodically. Both trees used were co-located at Joint Base Lewis-McChord, Washington and were approximately the same size. The first device was north facing and the second was south facing. Both energy harvesting devices had full exposure to the sun during the day.

The results were promising and prove the viability of a tree based TEG system, however there are still many improvements left to be made. More research must also be done on the thermal gradients between tree core and exterior in various climates and locations.

The remainder of this paper is organized as follows: Section 2 introduces the Experimental Energy Harvesting System and thermoelectric generation in details. Section 3 presents the methods used to run the experiments, and section 4 describes the experimental results. Section 5 explores possible future directions, and section 6 concludes the paper.

2. Energy Harvesting System

Trees around the world attempt to maintain a constant internal temperature of 21.4° Celsius as seen in [4]. It is show in [3] that the temperature between the core of the tree and the ambient outside environment creates a temperature differential during the rising and falling temperatures throughout the day. This is illustrated in figure 2.

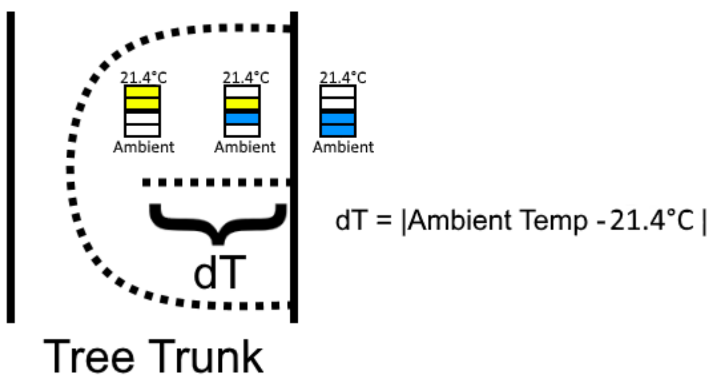

Figure 2. Temperature difference inside a Tree Trunk.

One way to take advantage of this phenomenon is to use a TEG. TEGs use the Seebeck effect which works on the principle that N-doped metals in series with P-doped metals will induce an electrical current when there is a temperature difference (ΔT) between the surface of the dissimilar metal's junction [3]. The Seebeck Coefficient is the voltage generated by the TEG per degree of difference between the faces of the TEG (V/ΔT). The structure of a TEG is illustrated in figure 3.

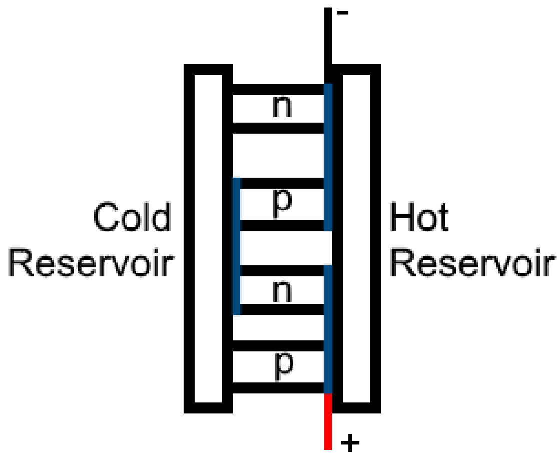

Figure 3. Thermoelectric Module internal structure.

TEGs are manufactured square panels that come in different sizes and quality. In order to leverage its properties with the tree temperature differential, one face of the TEG must be at the temperature of the core of the tree and the other side must be at the ambient temperature outside the tree. The orientation of the TEG was determined by comparing the temperature during the day or night and the internal tree trunk temperature.

3. Methods

3.1 Open-Circuit Voltage

The goal of the first experiment was to test the open circuit voltage of a TEG subjected to the thermal differential between the core and outside of a tree trunk. A 190mmLx19mmR standard aluminum rod was chosen from a local supplier and the end of the rod was milled to a point. The rod was then embedded in the trunk of a healthy 650mm diameter Ponderosa Pine tree such that the end of the rod was flush with the bark on the exterior of the trunk. To ensure that there was no air between the rod and the tree, a pilot hole half the diameter and two thirds of the length of the rod was drilled into the tree, and the rod was hammered into the hole. It is important for the rod to be sealed in the tree to prevent outside temperature from influencing the interior of the tree and to prevent pests from entering the interior of the tree. Care must be taken not to significantly deform the end of the rod when driving the rod into the tree.

The "Hot" side of a CP60233 20mm TEG was fixed to the end of the aluminum rod with thermal paste on the face and caulked around the edges to prevent outside temperature from influencing the temperature of the rod. A 20mm heatsink was attached to the "Cold" side of the TEG that was exposed to ambient air. To determine which side would be exposed to ambient temperature, Equation 1 was used. It was determined that during our experiment the greatest temperature gradient would occur at night when ambient air was cooler than the interior of the tree, so the "Cold" side of the TEG was exposed to air to maximize voltage during that period. Table 1 demonstrates the calculations used to determine TEG orientation.

$$\boldsymbol{T_{Max} = |T_{Int} - T_{Ext}|}$$

Equation 1. T_{Max} used to orient the TEG.

Time of Day	$T_{Max} = \lvert T_{Int} - T_{Ext} \rvert$	**July 6th, 2019, JBLM, WA**
Day Forecast	$\boldsymbol{T_{Max} = \lvert 21.4°C - 26°C \rvert}$	4.6° C
Night Forecast	$\boldsymbol{T_{Max} = \lvert 21.4°C - 16°C \rvert}$	5.4° C

Table 1. T_{Max} found to be greater at night. Cold side will face away from tree.

The positive terminal of the TEG was plugged into an analog input of an Arduino Nano platform and the negative terminal was plugged into the ground of the Arduino. The ADC on the Arduino was used to convert the open-circuit voltage of the TEG into a digital number, and this number was then sent through the serial port to a Raspberry Pi, where the time of the reading and the voltage reading were saved every second. The Arduino and the Raspberry Pi were powered by an Adafruit Powerboost 3000C connected to a 6000mA-hour LION battery, which powered the module for approximately 23 hours. The entire module was enclosed in a 3D printed shell as shown in Figure 4(a).

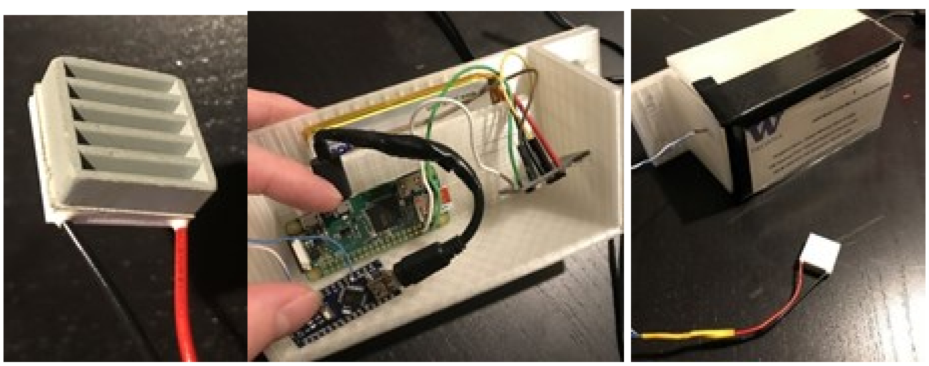

Figure 4. (a) Hardware for first experiment.

The module was installed in a Ponderosa Pine tree at JBLM on July 2nd, 2019, as seen in figure 4b, at approximately 2PM. The module was turned on and began recording data at 2:39PM. The module ran until the following day at 1:37PM. The data was retrieved, and a new battery was installed on July 6th, and the module began taking data at 12:17PM. The module ran and recorded data until 11:11AM the following day. The entire module was retrieved on the 8th of July.

Figure 4. (b) Hardware installed for first experiment (Names & Numbers blurred).

3.2 Voltage Across a 1 Ohm Resistor

The goal of the second experiment was to measure the voltage across the TEG when a 1-ohm resistor was inserted between the terminals of the TEG. With this data, current and power supplied by the TEG could be found. Temperature sensors in the tree and outside would be compared to the voltage generated and used to calculate the Seebeck Coefficient. Much like the previous experiment, an aluminum rod was embedded in a Ponderosa Pine and a TEG was fixed to the end of the rod. In this experiment a 10mm TEG was selected. The data was saved on a Raspberry Pi Zero and the whole module was powered by an Adafruit Powerboost. A 1-ohm resistor was chosen to match the 0.5-ohm resistance of the TEG plus an approximation of the output resistance added by the low thermal conductivity of the tree. Because the low voltage of the TEG a NJU7024 Op Amp was used to amplify the voltage across the resistor to increase the resolution of the ADC. The positive terminal of the TEG was connected to one end of the 1ohm resistor, and the negative terminal was connected to the opposite end of the resistor and to ground on the Adafruit Powerboost, which was being used as a single ended supply for the OP AMP. The positive terminal of the TEG was the input of both an inverting and noninverting amplifier on two of the four Op Amps on the IC. The outputs of the Op Amps were connected to two of the input terminals of the MCP3008 ADC, which was chosen rather than the Arduino Nano to conserve power. In this way, the voltage across the TEG would be amplified and converted to binary, regardless the direction of the heat differential across the TEG.

To measure the thermal differential across the TEG, one LM35 temperature sensor was embedded in a channel milled into the aluminum rod and another was fixed to the bark of the tree near the TEG. The Powerboost powered the temperature sensors, and the sense voltage outputs were plugged into the input terminals of the MCP3008. To keep accurate time the RCF8523 RTC was installed on the I2C pins on the Raspberry Pi. To increase the duration of the experiment, an ICM7555 timer in astable mode was installed in the module. The output of the timer was plugged into the enable pin on the Powerboost. The 7555-timer circuit was built such that the enable signal would be on for approximately 3 minutes, and off for approximately 16 minutes. When the enable signal turns on, the Powerboost turns on and supplies all the components with power. The Raspberry Pi saves data from the MCP3008 for two minutes before shutting off. After the enable signal turns off, the Powerboost turns off and no power is supplied to any of the components, except for the timer, which is powered by the battery itself. This extended the battery life of the module to over three days. The module was soldered to a pin board, figure 5, and placed in a plastic container that was fixed to the tree.

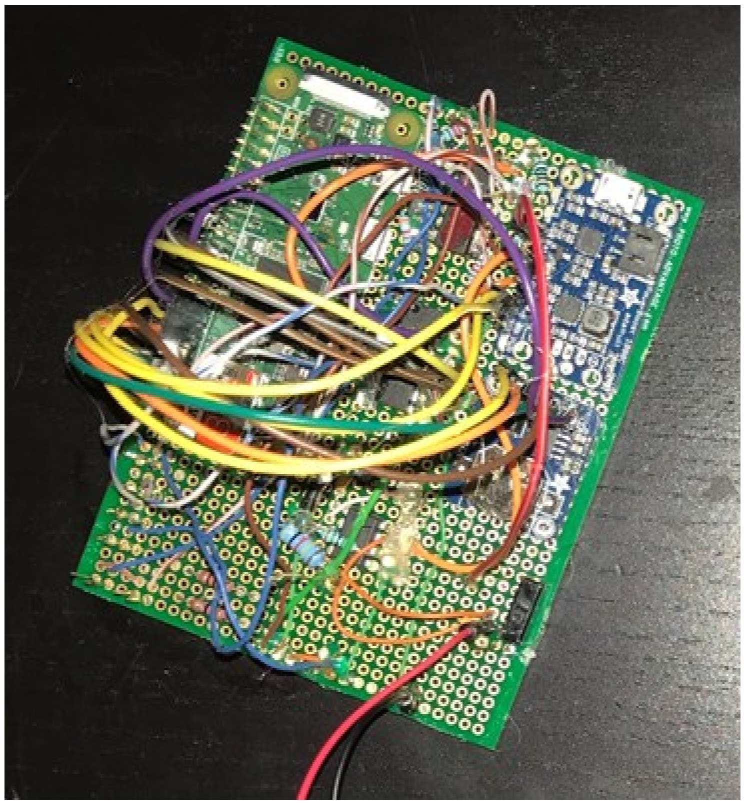

Figure 5. Hardware of Experiment 2: Raspberry Pi, RTC, 555 Timer, On-Off Switch, Powerboost 1000c, Op Amp, ADC, 1 Ohm Resistors

The accuracy of the Op Amps and TEGs was measured after the module was built. The voltage saved by the Raspberry Pi was compared to the voltage found using a lab digital multimeter. The TEG was held against warm lab equipment and removed to change the voltage generated by the TEG. The maximum difference between the recorded and actual voltage was .280mV, and the average difference was .098mV, as seen in figure 6.

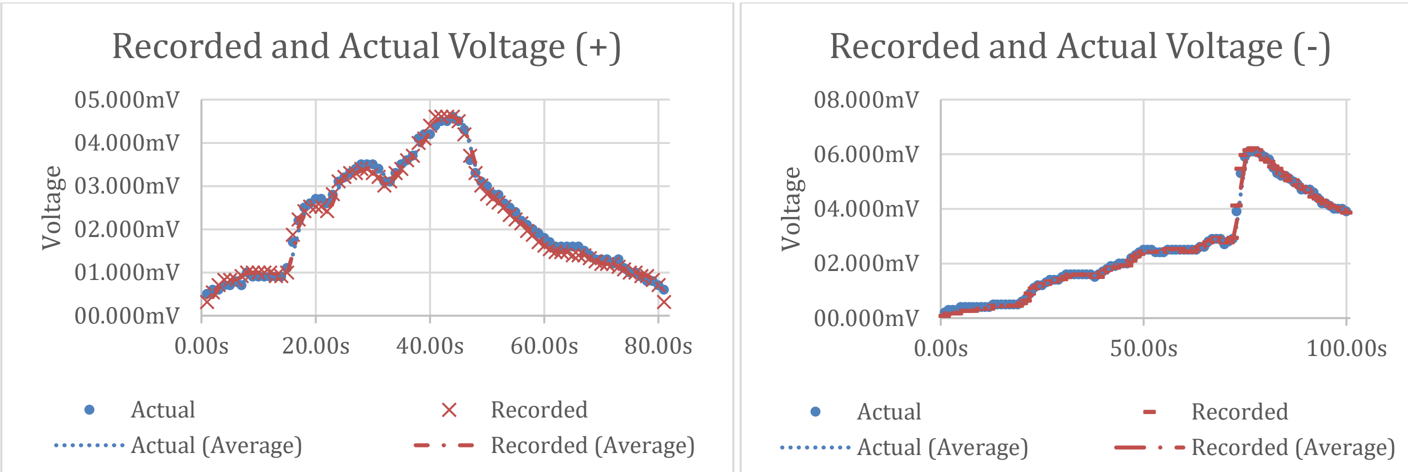

Figure 6. TEG voltage read by lab equipment and voltage recorded by Raspberry Pi

The module was installed in a Ponderosa Pine near the tree used for the first experiment. The module was turned on and began saving data at approximately 12:30PM on August 13th, 2019. The battery was changed periodically over the course of the week and the data was collected on August the 20th.

4. Experimental results

4.1 Open-Circuit Voltage

During the first session, the module measured a spike in voltage across the terminals of the TEG starting at approximately 00:00 on 7/3/2019 that lasted for approximately 10 hours. The average voltage was 2.16mV, with a maximum voltage measure of 4.09mV. As can be seen in figure 7a, during all other hours of the first experimental session, no voltage was measured. This is due to the limitations of the Arduino Nano; the Arduino Nano ADC can only convert positive analog voltages to digital values. During the second session the module measured a voltage spike starting at approximately 23:00 hours on 7/6/2019 that lasted for approximately 11 hours. The average voltage was 2.01mV, and the maximum voltage measured was 4.52mV. Local temperature data was acquired for the duration of the second experimental session. The temperature spike occurred after a 4°C temperature drop, from 19°C to 15°C, and ended when the temperature rose back to 19°C, as seen in figure 7b.

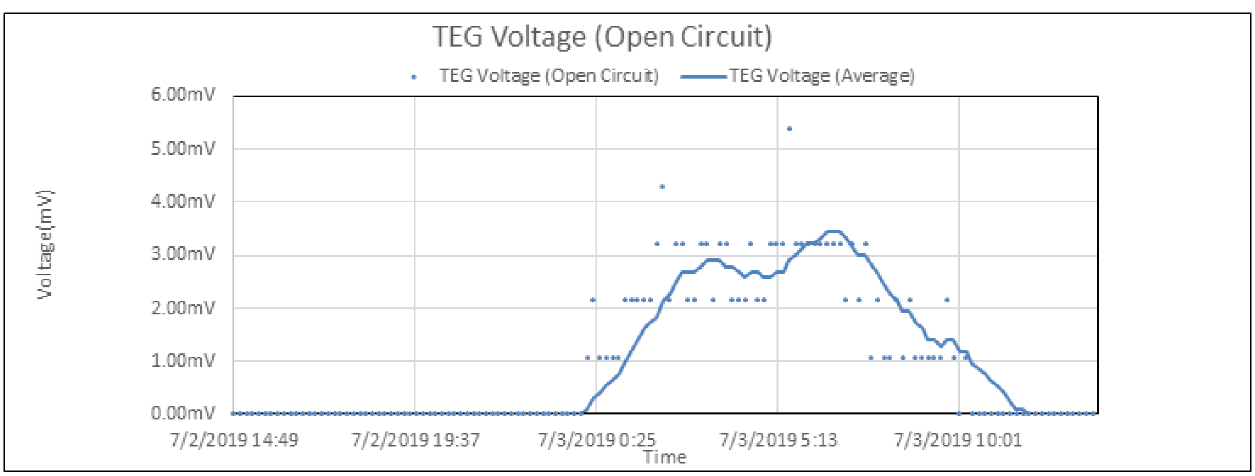

Figure 7a. Voltage vs Time Graph of Experiment 1 session 1.

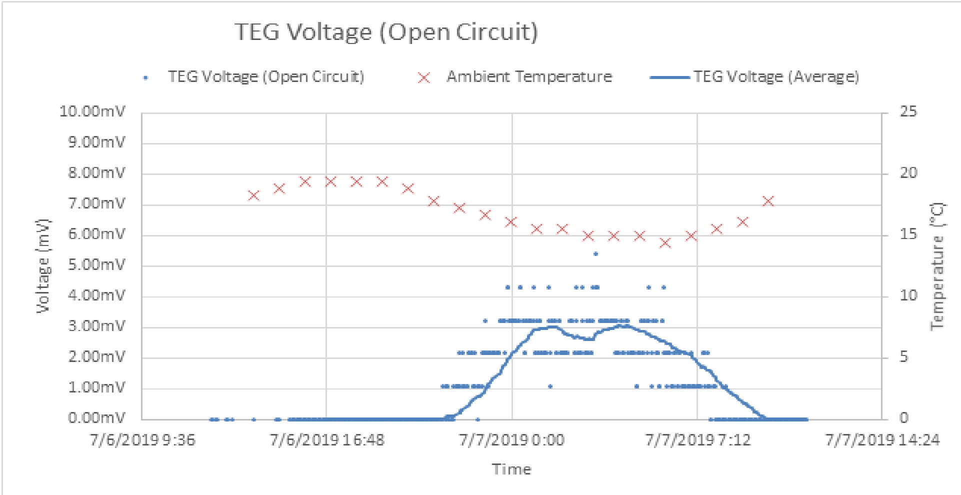

Figure 7b. Voltage and Temperature vs Time Graph of Experiment 1 session 2.

4.2 Voltage Across a 1Ohm Resistor

The temperature sensors ran for approximately two days before they began to fail, while the rest of the module ran as expected for the duration of the experiment. The maximum recorded voltage during the day was 6.8mV, and the maximum recorded voltage at night was -3.789mV, as shown in figure 8a. The average voltage for the duration of the experiment was 1.79mV. The temperature of the rod averaged at 22.6°C for the duration of the experiment, as seen in figure 8b. The temperature of the rod increased by a few degrees when the ambient temperature rose to 45°C and fell a few degrees when the ambient temperature fell to 14°C, which is consistent with the results found by Helliker [4]. By comparing the temperature data to the voltage data, the Seebeck Coefficient was found to be -0.259mV/°C while the ambient temperature was cooler than interior tree temperature. When the ambient air was warmer than the interior of the tree, the Seebeck Coefficient was found to be .207mV/°C.

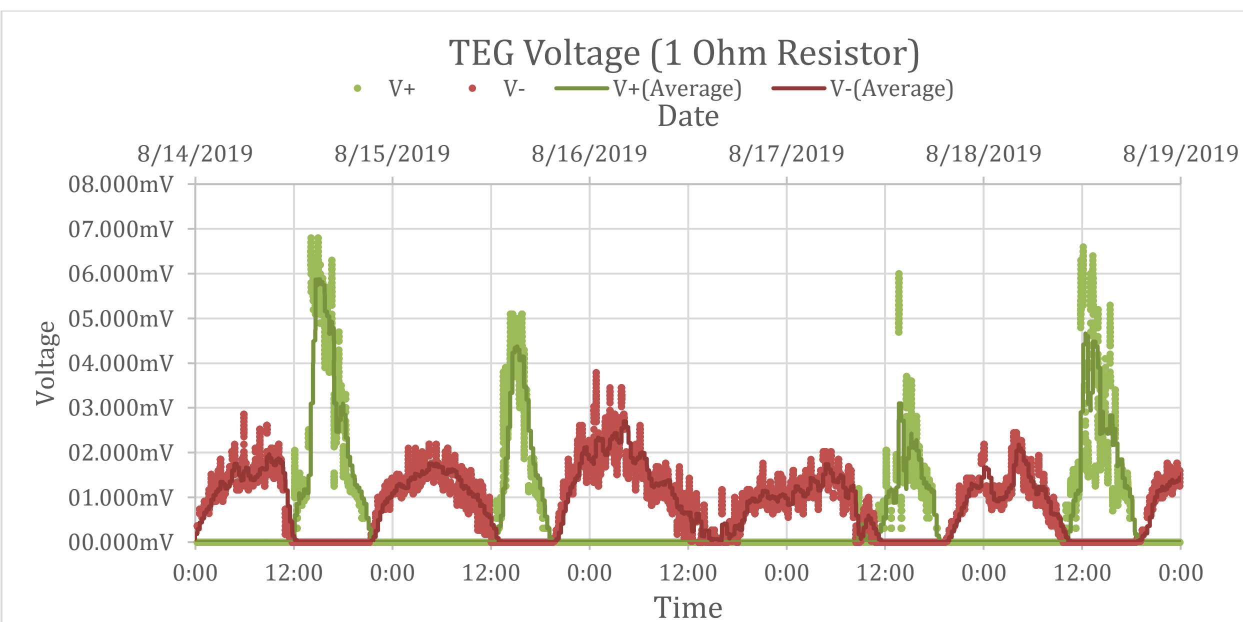

Figure 8.a Experiment 2 – Voltage

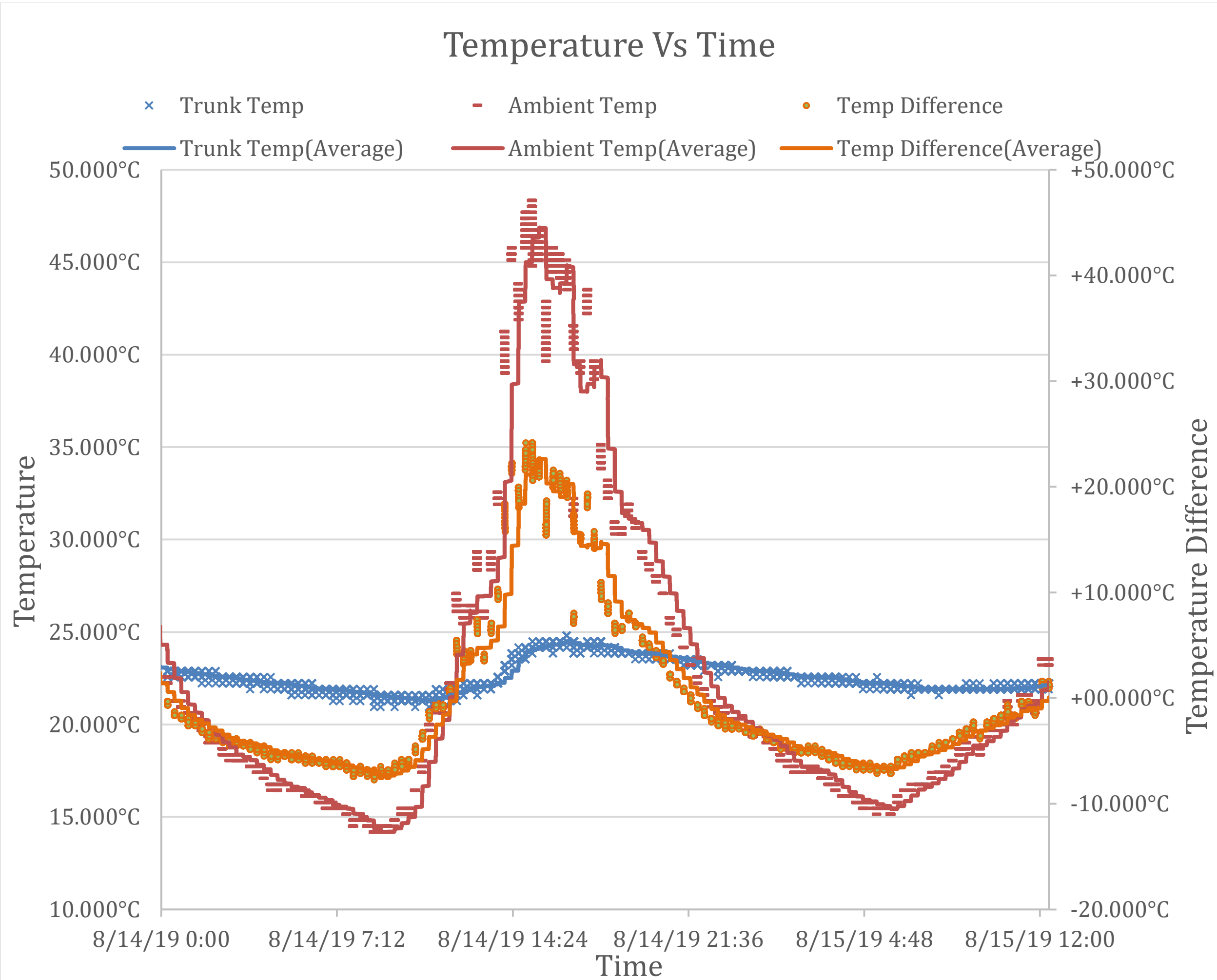

Figure 8.b Experiment 2 – Temperature

5. Future Direction

The results of both experiments were promising considering the simplistic apparatus design. With a more efficient design and better materials the Seebeck Coefficient will increase, resulting in a higher voltage per degree of difference and thus a higher average power generated. Future research should consider the characteristics of each tree species available and the environment they inhabit. Tree density, fluid-dynamics, size, and temperature difference are among some properties to consider.

Using the load across the TEG, 1 Ohm, and the average measured voltage, 1.79mV, the average power is calculated to be 3.207uW. While voltage is negative when the ambient temperature is higher than the interior temperature of the tree, this could be solved with a rectifier circuit as demonstrated in [5]. The Low Power CO TIDA-00756 sensor by Texas Instruments [6] is designed to run for 10 years with a CR2032 coin cell battery. The sensor uses the Zigbee protocol and Bluetooth to transmit data and takes temperature and CO measurements. The average power consumption of this device is 6.45uW, which is twice than the power generation of the current TEG module. However, using the data gathered during these two experiments and local average temperature data, the average power generated during each month can be predicted. While the hottest time of the year may seem like the best time to use the module, in Western Washington the largest temperature differential occurs in winter. Using the calculated Seebeck Coefficient of 0.259mV/ΔT and the average temperature in the Northwest US in January of -1°C, as reported by NOAA [7], the predicted TEG voltage is 5.8V. With a 1 Ohm load this would result in an average power of 33.7uW.

Currently available TEGs vary in sizes and efficiency. Future experiments should test these against varying diameters of rods. Surface area vs resistance should be researched. Depth increased the temperature difference between the tree and the ambient temperature [3]. Thus, one might consider an aluminum rod that has TEG's in series, inserted at intervals inside the tree to increase the yield, as illustrated in figure 9. Custom design work will need to be done in order to make sure the rod and all attached components stay undamaged during the installation process. A problem may arise where there will not be enough compartmentalization between each TEG and thus reduces the efficacy. However, if depth is a factor this may be worth exploring rather than a single TEG at the end of the rod.

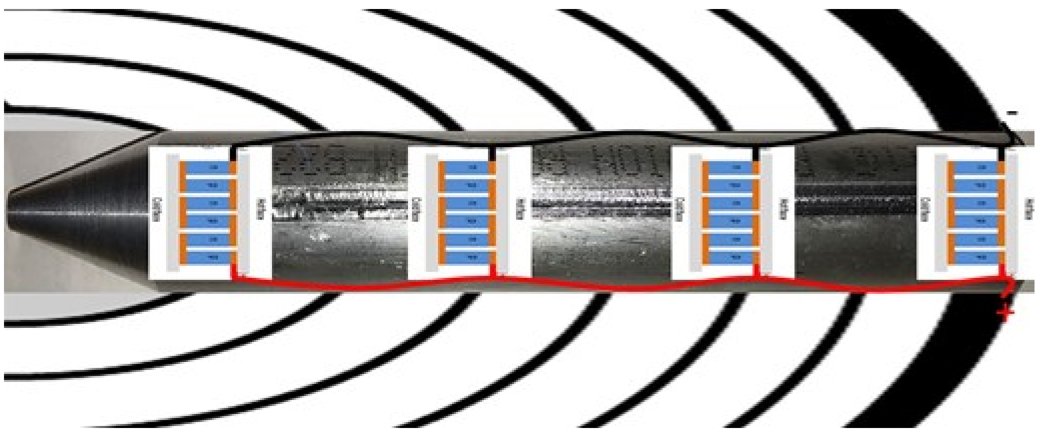

Figure 9. Possible Future Experiment 1.

Research was conducted into thermocouples as they have a cylindrical shape more advantageous to the research at hand; however, these are designed to operate as temperature sensors rather than generators and are not as efficient as TEGs in voltage generation. However, a thermocouple wire is available and could be useful for a proof-of-concept design as illustrated in Figure 10.

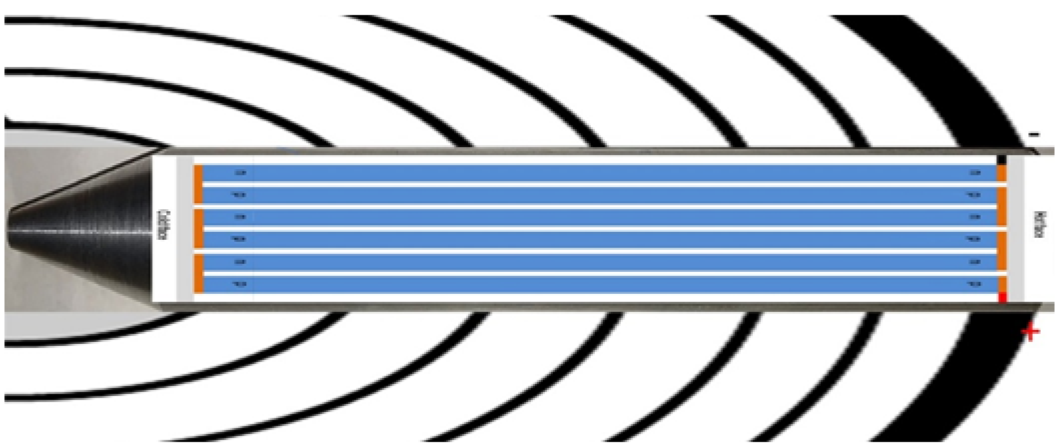

Figure 10. Possible Future Experiment 2.

The second experiment resulted in a maximum of 5mV across a 1-ohm load that is not enough to power current day sensors and transmit the data. The next step is to use adapted circuits to reach the required threshold of usable power. A Joule-Thief circuit will store the energy in capacitors and release it in intervals allowing for higher potentials. Impedance matching and capacitor leakage will be the main hurdles to overcome.

If the energy harvester is the sole source of power, given the current data, it may be possible to power sensors with extremely low power communication chips that communicate with a central node. This central node would likely be powered by more conventional means and transmit for a longer distance. If energy harvesting is not enough for the given sensor nodes, an energy-harvesting device may be used to trickle charge a battery at such a rate to sustain the battery long term. Another viable option is to install multiple energy harvesters in a single tree and connect them in series. More research needs to be done regarding trees ability to sustain these rods and mechanisms.

The most promising future direction is deployment of these TEG modules in trees in cold climates and during cold seasons, especially in Western Washington. If the internal temperature of the tree stays consistent the module will generate the most power in this region during December and January.

6. Conclusions

While average power generated by the system is relatively low, this will increase with further development of the energy harvesting system and environmental optimization. Increasing the Seebeck Coefficient by using alternate module configurations and deploying the module in colder climates will increase the average power generated by the module. The module is not far from generating enough power to run simple sensor systems, and the increase in average power will allow this module to power a wide variety of IOT sensors.

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