THERMOELECTRIC ENERGY GENERATION FROM BIOMASS: AN INNOVATIVE PROPOSAL FOR A SMALL SCALE SOLUTION

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Abstract
Throughout the world, millions of people are living unconnected from a central source of energy. These people typically utilize biomass fires to produce heat and light. If used incorrectly, this method of energy production can produce fumes that kill thousands of people annually. This has led the scientific community to search for methods to improve the technology. This project aims to create a method of energy production that does not encroach on any existing way of life or require additional infrastructure. The theoretical design of this device allows the continued use of biomass while also transferring noxious fumes out of homes, thus saving lives. While the final design does require ice for maximum efficiency, it can still be used in areas where another heat sink or a large temperature difference is readily available. Despite some limitations, this design shows promise for the future of off-grid energy generation.

Introduction
The technology behind this design, thermoelectric plates, are currently utilized to cool and heat various appliances, like some refrigerators and heaters. Running an electric current through these plates creates a temperature difference between the two sides. In contrast to these devices, this project will be running the plates in the opposite direction: using existing differences in temperature to create energy. While this specific strategy is not unique to this project, applying it to remote communities through biomass is. The decision to use thermoelectric technology was made because it requires no mechanical energy to create electricity. This would be beneficial in that fewer mechanical failures would occur, and less maintenance will be necessary.

As the world shifts from its use of natural resources to renewable energy, the need for renewable energy solutions has increased rapidly¹⁻⁵. According to the research conducted by the International Energy Agency, roughly 2.5 billion people burn biomass inside their homes. They do so for cooking, heat, and light as an alternative to electricity. Each year, thousands of people die from the fumes created from this practice⁶, making it a widespread problem. This project is intended to help people in need by protecting lives and providing energy to people off of the grid. A thermoelectric generator (TEG), also called a Seebeck generator, is a solid-state device that converts heat flux (temperature differences) directly into electrical energy through the Seebeck effect. Thermoelectric generators function like heat engines, but are less bulky and have no moving parts.
According to the Seebeck effect, when heat is applied to one of the two conductors or semiconductors, heated electrons flow from the heated surface toward the cooler one [Figure 1]. If the pair is connected through an electrical circuit, direct current (DC) flows through that circuit. The voltages produced by the Seebeck effect are small, usually only a few microvolts (millionths of a volt) per kelvin of temperature difference at the junction; however, if the temperature difference is large enough, some Seebeck-effect devices can produce a few millivolts (thousandths of a volt). Numerous such devices can be connected in series to increase the output voltage or in parallel to increase the maximum deliverable current. Large arrays of Seebeck-effect devices can provide useful, small-scale electrical power if a large temperature difference is maintained across the junctions.

![Figure 1: Semiconductor Thermocouple Seebeck Effect Diagram](image)

Method and Approach
Originally, this project was intended for use in remote areas without access to electricity. The group intended to make burning biomass safer and more efficient while generating electricity from the process. This design would be most practical in cold climates where a greater temperature difference is available, thus creating more electricity than would be possible in warmer climates. Once the decision had been made to develop a Thermoelectric Generator, the desired characteristics and constraints were considered.

The three variations looked at included a version with the thermoelectric plates sandwiched between the ground and a fire [Figure 3], a version with a metal pipe that extends below ground to utilize the cold dirt there [Figure 4], and a version that utilizes ice water above the fire [Figure 5]. These designs are discussed in more detail in the Initial Design. The group determined that safety was the first priority, followed by fuel availability and voltage output. Despite the fact that our final design had a very poor rating in fuel availability, its benefits clearly outweigh this drawback. Its voltage output will be the greatest due to the larger heat difference, and it will be much easier to install and use.
Initial Design
The initial design of the Thermoelectric Generator [Figure 2] harnessed the temperature difference between the furnace and the ground. The cool surface of the plates would touch the ground, while the hot surfaces would be flush with the inside of the furnace, thus gaining heat from the fire. Originally, it was assumed that the temperature difference in this design would be enough to produce voltage, but after some reconsideration, this presumption was deemed incorrect, as a more effective heat sink was needed. In addition, the ground is of variable temperature depending on the environment. This design did fulfill the majority of the constraints; however, the voltage output needed improvement, so further iterations of the design were created.

Alternate Design
The next version of this design, shown in Figure 3, stemmed from the same idea. In this version, a metal pipe would be inserted a meter below the ground. The thermoelectric plates’ cool surface would rest on the cool earth, and the hot surface would be in contact with a thin copper rod that stretched to the bottom of the furnace body. The copper rod would transfer the heat from the furnace body to the thermoelectric plates. This idea was not carried out, because this design would still not be very effective in producing voltage. In addition, the durability, ease of installation, and practicality would not be as effective as desired.
Clarification
To comprehensively display the thermoelectric generator, it has been split in three parts. The first part, the final design, demonstrates the ideal version of the generator. The second part, the proof of concept, proves the scientific theory behind the design and allows for the collection of data. The resultant data supports the claims made in this paper. The third part, the prototype, serves to demonstrate an effective version of the final design, created with materials and resources accessible to the common person. This prototype can be applied in the real world. Together these three parts properly present the thermoelectric generator.

Final Design
The final design [Figures 4 and 5] is very similar to the original version; however, changes were made in several areas. First, the exhaust tube was moved to the side of the furnace body, the walls of the furnace were extended to create a basin for the heat sink to rest on top of the dividing surface, and a small valve was added to allow for drainage of the heat sink once it has been melted. In addition, between the furnace body and the basin, a small tray [Figure 6] can be inserted and removed. The tray holds the thermoelectric plates and their wires, connected in a series circuit, and protects them from heat of the fire and the liquid of the basin. Finally, small air holes are located on the opening hatch to allow for air to flow in.

This design harnesses energy from the difference in temperature of a chosen heat sink and fire. It is more efficient than previous designs because it allows for both the hot and cold temperatures to be created inside the furnace. In addition, this design can be controlled with more accuracy than the previous designs because the quantities of biomass and the chosen heat sink can be controlled. It is also easier to install, maintain, and create. The ideal model would be created out of metal and manufactured in a place where the complexity of design could be completed efficiently and effectively.

Figure 5: SolidWorks Final Design
Figure 6: SolidWorks Final Design (Tray)
**Proof of Concept**
The proof of concept tested and proved the theory behind this project and helped prove that it would function on a larger scale. A procedure was created and used to collect and observe data on the voltage output from the temperature difference between ice and steam over time [Appendix 1]. Even at a relatively small temperature difference of 100°C, voltage was generated. The results from this experiment are discussed in detail in the *Data Collection* section of this report.

**Prototype**
Because the equipment was not available to produce the final design, the prototype was created using different materials. The elements used included plaster of Paris, play sand, water, and pre-made parts including a metal bucket, a pan, and a ceramic pot. To make and test the prototype, a set procedure was followed [Appendix 2]. The prototype has a basin made of five parts plaster of Paris, five parts sand, and three parts water mixed together in a metal bucket. A metal pan sits on top of the metal bucket, leaving slight openings for fumes to escape. The thermoelectric plates sit on top of the metal pan while the ceramic pot sits on top of the thermoelectric plates. Crushed ice is placed inside the ceramic pot, and wood chips are set into the basin and burned. The ceramic pot loses heat to the ice and the metal pan absorbs heat from the fire, which produces the temperature difference that generates energy. Instead of attaching a battery, the prototype was attached to a multimeter to collect data.

When running the prototype experiment, the distance between the thermoelectric plate and the flames needed to be increased, because the pan that covered the top of the furnace suffocated the fire. Increasing the airflow allowed the group to run the experiment successfully.

**Data and Analysis**
To analyze the effectiveness of the thermoelectric plates, data was collected on temperature and voltage. For the proof of concept, a regular thermometer was used to collect data on the cold ice water and the hot water. Data was also collected on the surface temperatures of the thermoelectric plate using an infrared thermometer. All temperature measurements were taken by hand at set intervals. The voltage was initially measured using a voltmeter composed of the SparkFun circuit kit and a program in Arduino to measure and record data points every second [Appendix 3]. SparkFun boards can only handle a maximum of five volts, so the circuit was designed with resistors to protect the board from damage if the thermoelectric plates generated more than five volts. While the SparkFun voltmeter was used to collect data during initial experiments, a professionally-built multimeter was used during the proof of concept for more accurate and reliable results.

A similar process was used to collect the voltage output of the prototype during its use. The only differences were that the trials lasted for shorter periods of time because the higher temperatures
put stress on the materials and that temperature data was not collected because the trials were too short and collecting data was too dangerous.

Graphical Representation of Critical Data

![Figure 7](Voltage vs. Time -- Trial Two)

**Figure 7**
Voltage vs. Time for Trial 2

![Figure 8](Voltage vs. Difference in Temperature -- Trial 2)

**Figure 8**
Voltage vs. Difference in Water Temperatures for Trial 2

![Figure 9](Voltage vs. Time -- First Trial with Prototype)

**Figure 9**
Voltage vs. Time for First Trial with Prototype

![Figure 10](Voltage vs. Time -- Second Trial with Prototype)

**Figure 10**
Voltage vs. Time for Second Trial with Prototype

After collecting data from the proof of concept, several conclusions were reached. Trial one data was not entirely conclusive because the experiment was not run very long. Trials two and three were more conclusive, as they were run longer. The data pictured above [Figures 7] exemplifies this key result of the proof of concept: as the temperature difference across the thermoelectric plate increases, so does the voltage.

Also included above is a graph [Figure 8] showing the relationship between the temperature difference and the voltage. This clearly shows an exponential relationship, meaning that small increases in the energy difference will increase the voltage substantially. The data above confirms that the prototype will create a quantity of energy worth harnessing. Additional graphs can be seen in Appendix 4, and the code that created them can be seen in Appendix 5.
When testing the prototype itself, it was observed that voltage output is less predictable with a biomass fire but that the average voltage output is significantly higher [Figures 9 and 10]. In addition, the prototype encountered some problems with the level of oxygen flowing in and out of the furnace. This was temporarily rectified in the lab using ring stands, but could easily be fixed by drilling ventilation holes in the side of the metal casing to the furnace, which would have been done if the ideal materials were available. Furthermore, the quality of these thermoelectric plates did not withstand the high temperature of the fire well. One plate became unsoldered from its wiring, and another’s wire began to melt. Thus, higher quality plates will be necessary when the design is implemented.

To power a typical household light bulb, one would need 120 Volts; however, to power the type of light that you would find in a car, one would only need 12 Volts\(^9\), so it is entirely reasonable to assume that a furnace with a few more durable plates could power a lightbulb.

**Improvements**

There are several improvements that could be made in relation to our final design. It could be made more efficient by reducing the amount of greenhouse gases released, improving the ventilation system, increasing the temperature difference, and allowing for ease of transportation. To enhance the prototype, more ideal materials should be used. The structure should be made completely of metal except for the tray, which must be made of a heat resistant material, such as ceramic.

Another way that improvements could be made is by paying more attention to the ethical debates involved. Spending more time to rework the design for a greener purpose would increase the value of the design.

**Conclusion**

Generating electricity from burning biomass is feasible based on the results of this project. The data collected from the proof of concept proves that energy generation is successful, even at relatively small temperature differences. With a larger temperature difference, like the one experimented on with the prototype, higher voltages can be generated.

The final design proposed can work anywhere, as long as there is a heat sink of some form, such as cold water or ice, but it would be most useful in cold locations. Applications include emergency situations, remote areas, and places where there is access to a large temperature difference. During the course of this project, the group was able to demonstrate that the final design functions as expected. In the future, better designs could be developed which would improve on the concept outlined in this paper.
Although the design works, there are a few constraints. The system cannot run constantly, as the cold water or ice will heat up after a given time, and hence will have to be replaced after certain time intervals to maintain the heat sink. Changing the water when it heats up will cause some fluctuations in voltage produced. When the heat sink increases in temperature, the temperature difference between the furnace and the cold surface will decrease, hence producing lesser voltage during that time and no voltage during times when the heat sink is being replaced. While the group did discover significant limitations with this design regarding the necessary temperature difference and the fragility of the thermoelectric plates, the results were also very promising from the perspective of future development of this concept.

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References
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8. Thompson, Grant, director. How to Make the Mini Metal Foundry. YouTube, 13 Jan. 2015.
Appendix 1: Proof of Concept Laboratory Procedure

1. Set up testing equipment.

2. Measure out 180 mL of tap water.
   a. Place tap water in a 150 mL glass beaker.

3. Measure out 150 mL (Trial 1) or 250 mL (Trial 2 and 3) of crushed ice.
   a. Place ice in a 200 mL glass beaker.

4. Put beakers onto the ring clamps.
   a. Place mesh grids on top of ring clamps.

5. Turn on the bunsen burner.
   a. Ignite bunsen burner.
   b. Start timer.

6. Take initial data for the temperature of the top and bottom surfaces of the thermoelectric plate and the voltage.

7. Every 10 s, take a measurement of the voltage.
   a. Record voltage data.

8. Every 60 s, take the temperature measurement of the thermoelectric plate surfaces.
   a. Alternate taking measurements for top and bottom plates.
      i. At 60 s, take the measurement for the top surface. At 120 s, take the measurement for the bottom surface. At 180 s, take the measurement for the top surface.

9. When the melted ice reaches 25°C, take a final measurement and reset experiment.

Materials

- Lab Setup
  - Bunsen Burner
  - Three Ring Clamps
    - One Small
    - Two Large
  - Two Beakers
    - One 150 mL
    - One 200 mL
  - Two Mesh Squares

- Testing Materials
  - Thermoelectric plates
  - Water (Liquid, Solid)

- Measurement and Data Collection Materials
  - Thermometer
  - Infrared Thermometer
  - Multimeter
  - Timer
  - Flint Spark Lighter
Appendix 2: Prototype Laboratory Procedure

1. Mix seven parts play sand and seven parts plaster of Paris until completely incorporated.
2. Quickly add five parts water.
3. When completely mixed, push the smaller plastic bucket into the center of the mixture.
4. Weigh small bucket down with water to keep in place.
5. Leave for six hours.
6. Remove plastic bucket from center.
7. Place structure into the fume hood.
8. Turn on fume hood.
9. Place ice inside metal pot.
10. Place paper and wood chips inside furnace.
11. Light fuel on fire.
12. Wait until fire has grown.
13. Place metal plate on top of bucket, leaving a small vent to allow smoke to escape.
14. Place thermoelectric plates on top of metal plate.
15. Place metal pot on top of thermoelectric plates.
16. Every 10 seconds, collect data on the voltage produced.
17. Run until fire dies down.

Note: When mixing, be careful to complete mixing in under 15 minutes, at most. After that, the mixture begins to set and will not be usable.

Materials

- Model Materials
  - Play Sand
  - Plaster of Paris
  - Bucket
    - Large (Metal)
    - Small (Plastic)
  - Water (Solid)
  - Circular Metal Plate
  - Porcelain Stew Pot

- Tools
  - Trowel
  - Wooden Stir Sticks
  - Diagonal Cutting Pliers

- Testing Materials
  - Thermoelectric Plates
  - Paper
  - Wood
  - Fume Hood

- Measurement and Data Collection Materials
  - Timer
  - Multimeter
Appendix 3: SparkFun Voltmeter Code and Diagram (as used during initial testing)

```cpp
int analogInput = 1;
float Vout = 0.00;
float Vin = 0.00;
int val = 0;

void setup(){
    pinMode(analogInput, INPUT); //assigning the input port
    Serial.begin(9600); //BaudRate
}

void loop(){
    val = analogRead(analogInput); //reads the analog input
    Vout = (val * 5.00) / 1024.00; // formula for calculating voltage out i.e. V+, here 5.00
    Serial.print(Vout);
    Serial.println("\n");
    delay(1000); //for maintaining the speed of the output in serial monitor
}
```
Appendix 4: Additional Graphical Representation of Data

Trial 1
Appendix 5: MatLab Code

%-----------------------------------Trial 1-----------------------------------
clear
voltagess=importdata('Trial1_Voltage.dat');
endtimeby10=size(voltages)*10;
timeby10=1:10:endtimeby10(1);
figure(1);
plot(timeby10', voltages, 'b');
hold on
fit=polyfit(timeby10', voltages, 3);
polyvalues=polyval(fit, timeby10);
plot(timeby10, polyvalues, 'r')
xlabel('Time (s)');
ylabel('Voltage (V)');
title('Voltage vs. Time -- Trial One');
legend('Trial One Data', 'Best Fit', 'location', 'southeast');
xlim([0 23*60]);

%-----------------------------------Temperature vs. Time-----------------------------------
watertemp=importdata('Trial1_WaterTemp.dat');
timeby1=0.5:1:endtimeby1(1);
figure(2);
plot(timeby1, watertemp, 'r');
hold on
fit=waterdifference=watertemp-icetemp;
fitwater=polyfit(timeby1', waterdifference, 3);
polyvalueswater=polyval(fitwater, timeby1);
plot(timeby1, polyvalueswater, 'g')
xlabel('Time (min)');
ylabel('Temperature (C)');
title('Water Temperature vs. Time -- Trial One');
legend('Warm Water', 'Cold Water', 'Approx. Temperature Difference', 'location', 'east');
xlim([0 23]);
ylim([-10 110]);

%-----------------------------------Top Surface-----------------------------------
toptyby2=importdata('Trial1_TopTemp.dat');
timetop=0:2:endtimeby2(1);
figure(3);
hold on
plot(timetop, toptemp, 'b.';
hold on
fittop=polyfit(timetop', toptemp, 2);
temptopfit=polyval(fittop, timetop);
plot(timetop, temptopfit, 'b');

%--------------------- Bottom Surface
bottomtemp=importdata('Trial1_BottomTemp.dat');
timebottom={0, 1:2:23};
plot(timebottom, bottomtemp, 'r.');
%--------------------- Best Fit
fitbottom=polyfit(timebottom, bottomtemp, 2);
tempbottomfit=polyval(fitbottom, timebottom);
plot(timebottom, tempbottomfit, 'r');

%--------------------- Temperature Difference
difference = tempbottomfit(2:13) - temptopfit;
plot(timetop, difference, 'g')

%--------------------- Label Graph
xlabel('Time (min)');
ylabel('Temperature (C)');
title('Surface Temperature vs. Time -- Trial One');
legend('Cold Side Data', 'Cold Side Best-Fit', 'Warm Side Data', 'Warm Side Best-Fit', 'Surface Temperature Difference', 'location', 'east');
xlim([0 23]);

%--------------------- Ratios
water_difference=watertemp-icetemp;
water_difference=water_difference(2:size(water_difference, 1));
dT = sort(water_difference);
coef_voltages = voltages(10:6:size(voltages, 1));
figure(5);
hold on
%--------------------- Best Fit
fitratio=polyfit(dT, coef_voltages, 2);
fitratio2=polyval(fitratio, dT);
plot(dT, fitratio2, 'r');
%--------------------- Set parameters for ratio graph
title('Voltage vs. Difference in Temperature');
xlabel('Difference in Temperature (C)');
ylabel('Voltage (V)');
xlim([min(dT), max(dT)]);
legend('Data', 'Quadratic Regression', 'location', 'southeast')

%--------------------- Save Graphs
print('-f1', 'Trial1_Graph_Vvt', '-djepg');
print('-f2', 'Trial1_Graph_Vvt_Water', '-djepg');
print('-f3', 'Trial1_Graph_Vvt_Surfaces', '-djepg');
print('-f5', 'Trial1_Graph_VvT', '-djepg');