Advancing Thermoelectric Battery Technology for Sustainable Energy Storage

Grant Proposal

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Contents

Executive Summary

Our dependence on fossil fuels over the last 200 years has led to deleterious effects on the world's ecosystem due to the byproduct production of greenhouse gases, primarily carbon dioxide. To combat this issue and to achieve a net-zero carbon footprint for energy, fossil fuel use is being replaced by renewable energy sources such as solar or wind. However, some renewable energy sources are intermittent, and energy must be stored so it can be available when needed.

The primary mechanism for storing energy is using batteries. Most batteries today store energy using chemical reactions. A common battery type uses a light metal called lithium and other rare earths as the primary material for storage. Lithium is usually strip-mined and manufactured with negative environmental impacts. There is a need for energy storage solutions that do not depend on environmentally destructive mining extractions. Different types of novel battery solutions are being pursued aggressively to solve this problem.

A new type of battery that would be useful is a thermoelectric battery that stores energy using heat. Such a battery would convert electrical energy into heat energy when there is an excess of renewable power. The heat energy could be converted back into electrical energy when needed. Advancing thermoelectric storage options as an alternative to chemical batteries could provide a scalable and environmentally friendly solution that could revolutionize energy storage.

Advancing Thermoelectric Battery Technology for Sustainable Energy Storage

To combat greenhouse gas emissions, the production of electricity using fossil fuels is being replaced by sustainable energy sources such as solar or wind. These energy sources require energy to be stored so it can be available when needed. Storage of energy is traditionally done using batteries based on chemical storage. These chemicals are obtained through mining and other methods that have negative environmental impacts. Storing energy thermally rather than by using chemicals offers easily scalable and environmentally friendly battery storage.

Thermal energy is starting to be used for energy storage. A recent thermal storage project in Finland is the world's first "sand battery" and can store heat at 500 ^{o}C for months at a time. (Puttkamer, 2022). One of the major advantages of this type of storage is that the storage medium (sand) is low-cost and environmentally friendly. This project utilized 100 tons of sand stored in a 7-meter steel container that was connected to the power grid using off-peak low-cost electricity to heat the sand using resistive heating. The output of the sand battery can be used to drive steam turbines to generate electricity, or the heat can be used directly for domestic heating requirements.

The Department of Energy (DOE) in the United States has launched the "Energy Storage Grand Challenge," which is a comprehensive program to accelerate the development, commercialization, and utilizing of next-generation energy storage technologies (*Energy Storage Grand Challenge*, n.d.). A subprogram area of this challenge is for "Thermal Energy Storage Technologies", focused on the research, development, demonstration, and deployment (ROD&D) for building applications. (*Thermal energy storage*, n.d.). Thermal storage is a key component of our energy storage systems of the future and an exciting area of research.

While thermal energy storage can deliver heat directly for building use, it is desirable to be able to use the stored heat energy and convert it back to electrical energy for general use in the building. In this concept, thermal energy storage acts like a traditional battery, charging from an electrical energy source (such as a sustainable source like solar or wind) and discharging when needed. The “charging” phase of the thermal storage would consist of heating a storage medium (such as sand or phase change material); this can be done using electricity through resistive heating. Also needed in the “charging” phase is the ability to cool another medium (such as water) to its freezing temperature to obtain a maximum temperature differential (ΔT). Typical large-scale methods for cooling use compressors and a gas that cools via expansion. A small-scale method can use the Peltier effect through a thermocouple junction of two dissimilar metals when a voltage is applied. One side of the junction cools, and the other heats. Commercial thermoelectric cooler (TEC) modules exist that are used for such devices as portable refrigerators and laboratory cooling. A TEC uses the Peltier effect to move heat from one side of the device to another, creating a temperature differential between the two sides. A study (Shi et al., 2023) shows the usage of Peltier devices to cool water.

Large-scale solutions for converting thermal energy to electrical energy would use a steam turbine or Stirling engine to drive a generating unit. For smaller scale uses, a thermoelectric generator can be constructed using Peltier devices operating in reverse mode, where a temperature differential is provided across the TEC module and a voltage is generated through the Seebeck effect. This voltage can be used to generate electricity for home use.

Section II: Specific Aims

This proposal’s objective is to obtain funding for conducting research, modeling, and building a scalable prototype of a working thermoelectric battery. The long-term goal is to improve thermoelectric materials and battery design for enhanced energy conversion efficiency.

The work I am proposing here will:

Specific Aim 1: Model the thermodynamic interaction of the battery to find an efficient design in the conversion of electrical energy to thermal energy and vice versa.

Specific Aim 2: Construct a working prototype given the optimal design produced by the model.

Specific Aim 3: Compare the model to the prototype to determine the predicted vs. actual performance of the system.

The expected outcome of this work would enable the prediction of the scalability as a supplemental energy storage for renewable energy and enable an assessment of the environmental benefits and sustainability of thermoelectric batteries.

Section III: Project Goals and Methodology

The methodology of the project is to:

1. Research relevant information in the field of thermodynamics and thermoelectricity.
2. Create a model of the thermoelectric battery using modeling software (i.e., COMSOL Multiphysics).
3. Test the model by constructing an actual device.
4. Extrapolate the device into real world usage.
5. The envisioned thermoelectric battery device shall be constructed as follows:

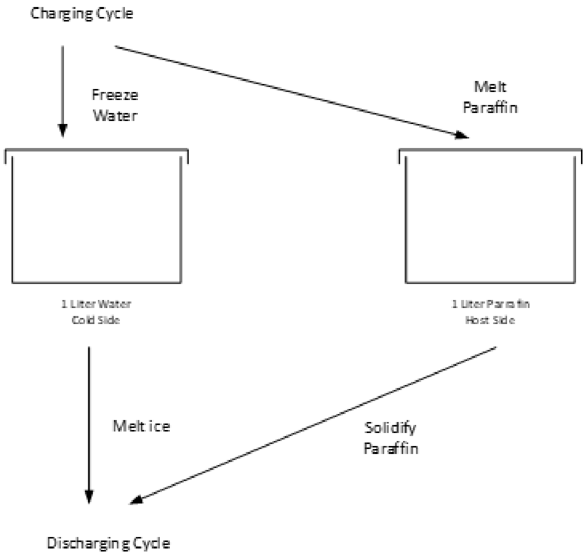

Figure 1: Representation of charging and discharging cycles of envisioned thermoelectric battery.

Two tanks, each holding one liter, shall be used. One tank will contain 1 liter of Water (H_20), and the other tank will contain one liter of Paraffin wax (C_nH_{2n+2}), both materials being phase change materials with different phase change temperatures:

- Water (H_2O) undergoes a phase change by freezing at 0 ^{o} C
- Paraffin wax (C_nH_{2n+2}), undergoes a phase change by melting between 52 ^{o} C and 62 ^{o} C.

When the battery is charging, the cold side of the battery (Water) will be frozen into ice and the hot side of the battery (paraffin) will be melting into a liquid. When the battery is discharging, the ice will melt, turning from ice into water, and the paraffin wax will solidify. The temperature difference between the hot tank and the cold tank will be used to generate electricity using a Thermoelectric Generator (TEG).

There are three specific aims as part of this project as follows:

Specific Aim #1: Determine an efficient design for a Thermoelectric battery using modeling software.

Specific Aim #2: Construct a working prototype given the optimal design produced by the model.

Specific Aim #3:Compare the model to the prototype to determine the predicted vs. actual performance of the system.

Specific Aim #1: Determine an efficient design for a Thermoelectric battery using modeling software.

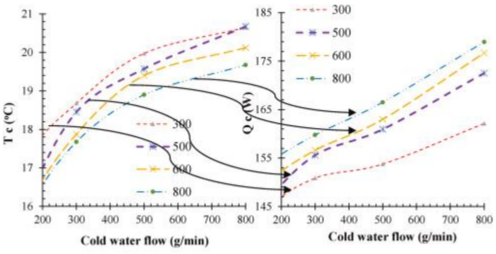

Figure 1.1 - From research on (shi et. al) the economic effectiveness experimental case study for instant cooling of water using Peltier module shows the delta temperature (delta T) and changes in energy in the water for given water flows at 150W constant power.

Justification and Feasibility. Computer modeling tools and calculations exist to allow for the study of thermoelectric (TEC) devices and heat transfer through various materials. These devices can convert electricity into heat and back to electricity. Using these tools to study a design for the thermoelectric battery will allow for the selection of the optimal voltage and current to power the device and the appropriate phase change materials to use for the battery.

Shi et al., (2023) shows the usage of Peltier devices to cool water, which is one of the target phase change materials for the study. Using Peltier devices to freeze the water is a key component of the thermoelectric battery, and this study provided information on the best way to do this. It included calculations of energy (Joules), the number of required Peltier devices, the number of required heat sinks, and required amount of electricity.

Another key component of the design is the selection of appropriate phase change materials for the hot and cold sinks. Zalba et al., (2003) created a comprehensive list of phase change materials along with the characteristics of each material that could be utilized in a thermoelectric battery application.

Summary of Preliminary Data.

Thermoelectric conversion using the Peltier effect requires careful consideration of the delta temperature across the device and the ability to drive phase change materials within the limits of these TEC devices (Alaoui, 2011). The goal is to have the highest differential temperature for the battery using a hot phase change material (e.g. paraffin) and a cold change material (e.g water). Alaoui, (2011) showed that

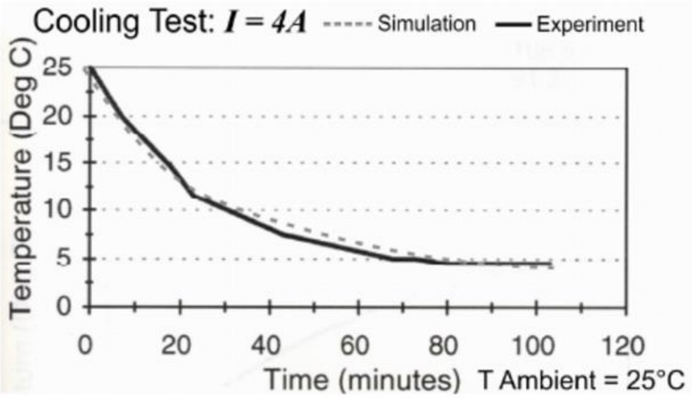

Figure 2 - the above graph was obtained using experiemental data and also modeled data (using Spice) showing the temperature of water coolled using a Peltier device with a constant input of 4 Amperes. This shows that a maximum of 20 DegC temperature difference can be acheived using the Peltier device, which will drive the selection of appropriate phase change materials for the battery.

Peltier devices have a limited ability to drive a Δ temperature across the device, in this instance a maximum Δ T of 20 ^{o} C is achieved (Figure 1). This limitation will drive the selection of the phase change materials and design of the overall device.

Zalba et al., (2003) studied thermal energy storage with phase change materials, heat transfer, and applications. Paraffin and water could be used, as water has a phase change of 0 ^{o} C. In contrast, paraffin mixtures can be formulated to have a phase change from subzero to 100 ^{o} C (Lin et al., 2020).

Expected Outcomes. The overall outcome of this aim is to have a thermodynamic model of the battery using thermoelectric generating devices and be able to quantify the design in terms of:

- Optimal cooling requirements, passive vs. forced cooling.
- Achievable Δ temperature
- Selection of Phase Change materials for hot and cold sinks of the planned battery based on achievable Δ temperature.
- Energy consumption (voltage and current)

This knowledge will be used for designing the optimal thermoelectric battery.

Potential Pitfalls and Alternative Strategies. I expect that the model will not exactly match the tested results. The strategy for the development of a complex model is to first create a simple model, i.e., a single thermoelectric device heating a simple material. This simulation can then be matched to a real-world example through testing. Once confidence is gained in the modeling tools and model, the model can be expanded to the full working battery.

Specific Aim #2: **Construct a working prototype given the optimal design produced by the model.**

Justification and Feasibility. To test the thermoelectric battery model, a working prototype shall be constructed to test the design principles learned in Specific Aim #1. This is a bridge to specific aim #3, where the model will be tested against the prototype unit. As no referenced studies exist that provide test results for the type of device envisioned, the construction of the prototype is broken down into three (3) specific phases, as follows:

- **Phase I** - Freezing water (target 1 Liter or 1 kg) using TEC modules.
- **Phase 2** - Melting Paraffin (target 1 Liter or 0.9 kg) using TEC modules or resistive heating.
- **Phase 3** - Thermoelectric Generator (TEG) using the Seeback effect.

Phase I - Freezing water (target 1 Liter or 1 kg) using TEC modules

The first phase of the prototype project will be to construct a device using Thermoelectric Cooler (TECs) to freeze 1 liter of water.

Summary of Preliminary Data.

To first understand a method in freezing water can be done, A paper “Rapid Water Freezer using Thermoelectric Module” (Khodegaonkar et al., 2019) that describes the construction of a device to freeze water was studied.

Thermoelectric devices (used in “Rapid Water Freezer using Thermoelectric Module”) are small devices that use the Peltier effect to transfer heat from the cold side of the module to the hot side. The device is constructed as shown and requires a DC input of +6V to +12V.

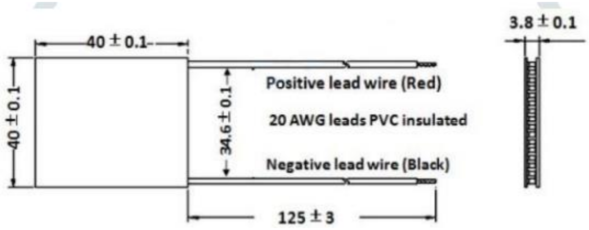

Figure 3: Diagram of thermoelectric device - Peltier module (Khodegaonkar et al., 2019)

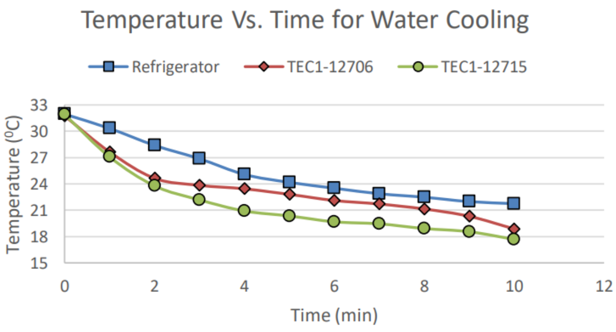

Figure 4: Graph of temperature vs. time for cooling with different methods - refrigeration, TEC1-12706 module, and TEC1-12715 module. (Khodegaonkar et al., 2019)

Various TEC modules can provide rapid

cooling of water using different input voltages and currents. A common type of module is the TEC1-12706 module, which is commonly available for about $4-$5 each. The reference paper shows tests conducted to freeze 0.5 liters of water using standard refrigeration and two types of TEC modules (12706 and 12715). From this study, TEC modules can cool water as rapidly as a standard refrigeration unit.

Khodegaonkar et al., (2019) provided a set of calculations to determine the number of TEC modules needed to freeze a given quantity of water in a given time. In the study, the target mass was 0.5 kg of water (1/2 liter), and the target freeze time was 1.5 hours. For my calculation, I would target 1 kg of water (1 liter) and 10 hour freeze time. The steps of my calculations are shown in Appendix 2.

From the calculated power requirement, the number of needed TEC modules can be calculated using the table in the referenced study for a given type of TEC module (Figure 5). The TEC module chosen for this project is TEC-12706.

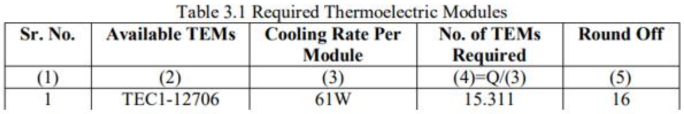

Table 3.1 Required Thermoelectric Modules

Sr. No.	Available TEMs	Cooling Rate Per Module	No. of TEMs Required	Round Off
(1)	(2)	(3)	(4)=Q/(3)	(5)
1	TEC1-12706	61W	15.311	16

Figure 5: Information regarding TEC1-12705 thermoelectric module, including power requirements for each module. (Khodegaonkar et al., 2019)

From the study, each TEC module requires 61W of power. Thus, the number of modules required is 11.4. This number is rounded to twelve (12) modules, as the cooling device described in the reference paper uses four (4) TEC modules per device. It should allow a freeze time for the water of about 9-10 hours.

A summary of the total joule's calculation is shown in Appendix 1.

The Phase I freezing device shall consist of a fan, a copper heat sink, a tin container to hold the 1 liter of water and shall follow the design presented in the paper as follows:

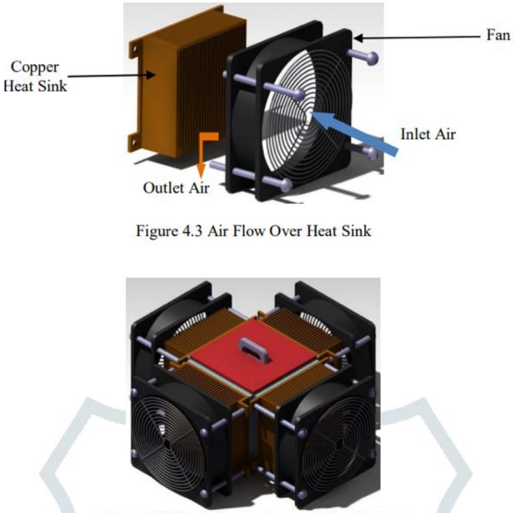

Figure 4.3 Air Flow Over Heat Sink

Figure 4.4 Final Thermoelectric Water Freezer

Figure 6: Water cooler configuration to be replicated for thermoelectric battery from referenced study. (Khodegaonkar et al., 2019)

Expected Outcome – The expected outcome of the Phase I of Aim #2 is to construct a device that will freeze 1 liter of water in 10 hours.

Potential Pitfalls and Alternative Strategies. – Although this phase of the project is expected to succeed as we are modeling the freeze device after a known study, it is possible the device will not perform as desired. If this is an issue, then I can look at the alternatives of:

1. Adding more TEC modules to freeze the water.
2. Substitute a higher efficient TEC module that provides a greater delta temperature.

Phase 2 – Melting 1 Liter of Paraffin Wax

The hot side tank of the battery will require the melting of 1 liter of paraffin wax while charging and allowing the paraffin wax to solidify while discharging. This will create a phase change in the hot side, allowing for maximum storage of energy.

Summary of Preliminary Data

In the previous phase, thermoelectric cooling modules (TEC modules) were used to create the ice in the cold tank. To create maximum potential heat energy in the hot tank, the paraffin wax will be melted using two simultaneous mechanisms:

- Excess heat transferred from the water-cooling effect of the thermoelectric cooling modules will be transferred to the paraffin wax.
- A resistive heating coil will melt the paraffin wax further as needed during the charging cycle.

The first step is to select a paraffin material that will provide the highest temperature, not exceeding a design limit of 70 ^{0}C (temperatures above 70 ^{0}C become dangerous and are outside the scope of this project). From the reference paper (Zalba et al., 2003) Table #4, the following paraffin wax material was selected as it is cost-effective and provides high melting point:

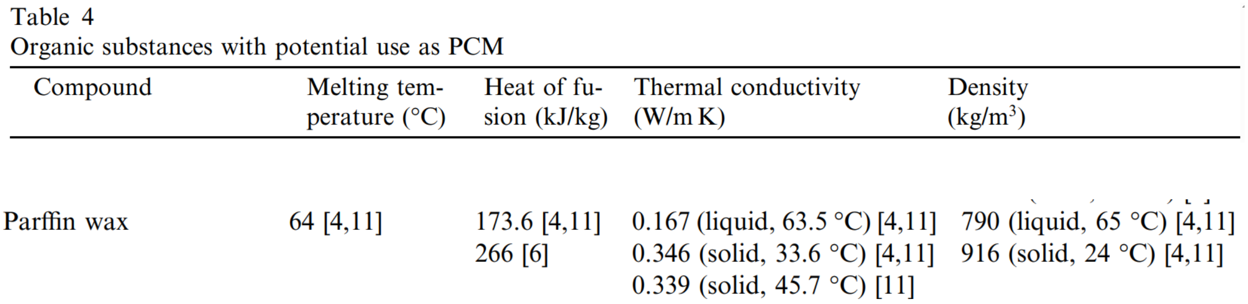

Table 4
Organic substances with potential use as PCM

Compound	Melting temperature (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Density (kg/m^3)
Parffin wax	64 [4,11]	173.6 [4,11] 266 [6]	0.167 (liquid, 63.5 °C) [4,11] 0.346 (solid, 33.6 °C) [4,11] 0.339 (solid, 45.7 °C) [11]	790 (liquid, 65 °C) [4,11] 916 (solid, 24 °C) [4,11]

Figure 7: Information regarding Paraffin wax (Zalba et al., 2003)

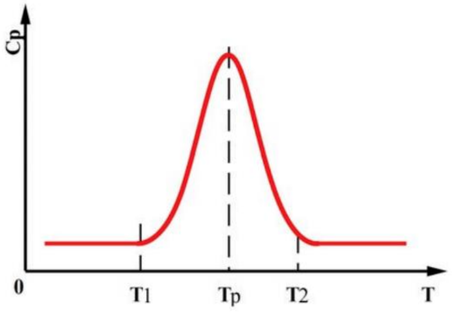

Figure 8.1: Temperature curve indicating a higher specific heat capacity in the phase-change temperature range. (Socaciu, 2012)

Per the reference paper (Socaciu, 2012), the paraffin wax will contain latent heat storage when heat is applied to the material by storing the heat as latent heat of fusion. In practice, the phase change of the material (melting) happens in a certain temperature range instead of at a specific temperature. The curve (in Figure 8.1) shows the specific heat capacity (c_p) and temperature (T) showing the curve of a specific phase change material.

The enthalpy (h) vs. temperature curve (in Figure 8.2) shows these two temperature points while melting the paraffin wax material. It is seen that in the temperature range [T1, T2], the c_p-T curve has a peak interval whereas the h-T curve shows a slope change according to the same temperature range due to the relationship between the h-T and cp-T functions. These graphs indicate the more energy will be required to create the phase change in each material.

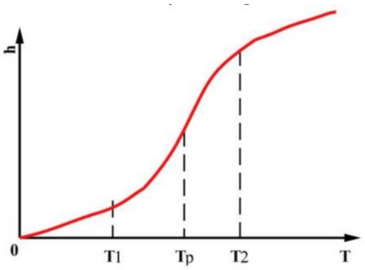

Figure 8.2: Temperature curve indicating that more heat is needed to go over the phase-change temperature range. (Socaciu, 2012)

The number of joules contained in a liter of paraffin can be calculated in a similar fashion to the number of joules to freeze one liter of water in Phase I. In this case, one liter of paraffin wax in equal to 0.93 kg of paraffin, so I used that value in my calculation.

A summary of the total joule's calculation is shown in Appendix 1, with individual steps shown in Appendix 3.

Heat transfer from the cooling device to freeze the water to the hot tank where the paraffin wax is melted is planned.

Tayssir et al., (2017) describes testing the melting of paraffin wax using a setup with a heater, a heat transfer coil, a container of paraffin, thermocouples providing temperature measurement in the paraffin material, and a personal computer (PC) collecting temperature data, as follows:

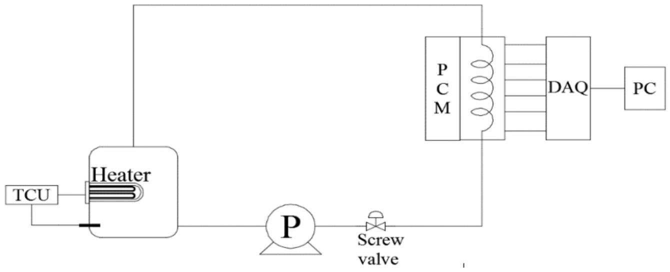

Figure 9: Testing setup to melt paraffin wax used in referenced paper. (Tayssir et al., 2017)

The paper provides different temperature vs. time curves for different Heat Transfer Fluid flow rates and input temperatures. It allowed me to design a specific temperature in which the paraffin could be melted in a specified time period. My planned battery solution uses a similar setup, and hence, an input temperature of the heat transfer fluid of 90 ^{o}C should provide melting time of about 600 minutes at a flow of the heat transfer Q of 15 liters per minute, as follows:

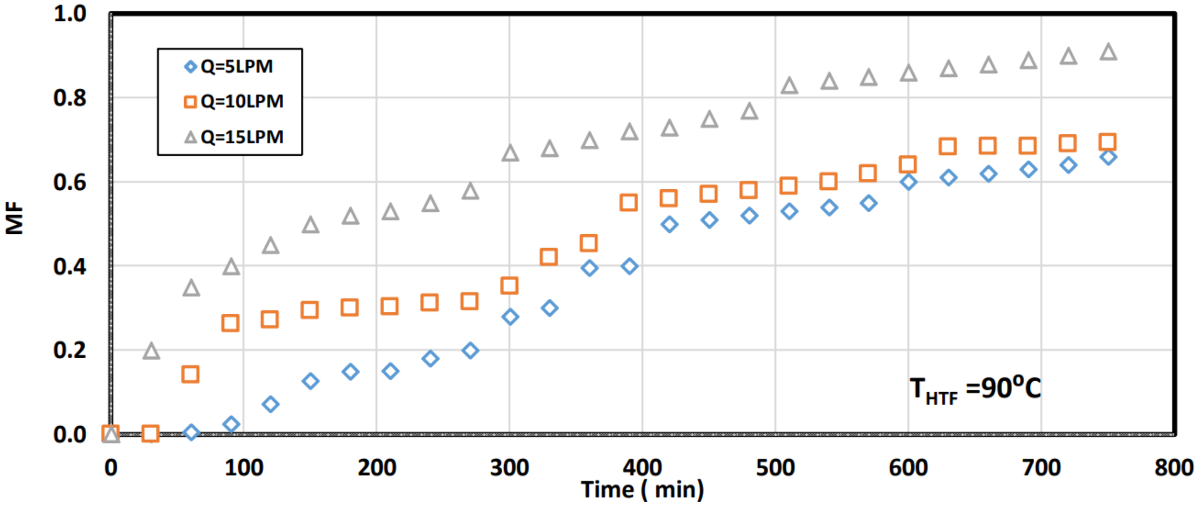

Figure 10: Percent of paraffin melted vs. Time at a specific temperature of 90 degrees Celsius (Tayssir et al., 2017)

- Mf – Percentage of paraffin wax melted
- Q (LPM) = Liters per minute transfer through the heat exchanger
- HTF – Heat Transfer Factor (temperature of heat transfer liquid)

Expected Outcome – The expected outcome of the Phase 2 of Aim #2 is to construct a device which will melt 1 liter of paraffin wax in 600 minutes.

Potential Pitfalls and Alternative Strategies. – Although it is expected this phase of the project will succeed as we are modeling the melting system after a known study, it is possible the device will not perform as desired. If this is an issue, then I can look at the alternatives of:

1. Adding more heating coils to melt the paraffin
2. Decreasing the resistance of the heating coil so it runs at a higher temperature.

Phase 3 – Thermoelectric Generator (TEG) using Seeback Effect

Once the heat energy has been stored in two energy tanks (cold tank containing ice at 0 ^{o}C and hot tank containing melted paraffin at 64 ^{o}C), we are now able to “discharge” the battery and use the stored heat energy to generate electrical energy. A thermoelectric generator (TEG) is required for the conversion.

Key to the battery performance is the delta temperature (ΔT – 64^{o}C) and the number of joules (825,040 Joules, calculated in Appendix 1) in the system.

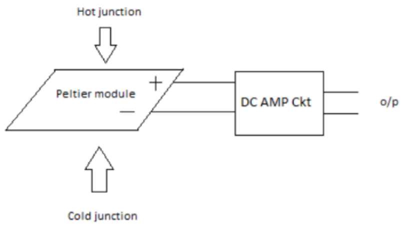

Figure 11: Diagram of Peltier devices and representation of Seebeck effect. (Kaphungkui et al., 2016)

Peltier modules shall be used for the thermoelectric generator (TEG) by reversing the Peltier effect using a heat and cold source on the hot and cold junctions to generate a DC voltage across the + and – sides of the Peltier module. This effect is called the Seeback effect and is the reverse of the Peltier effect.

The target paper used a Fresnel lens to amplify the sun’s rays onto a hot junction of a Peltier module, to demonstrate the use of heat to generate electricity directly (Kaphungkui et al., 2016). The subject used four (4) Peltier modules and four (4) heat sink plates to generate electricity. The target output of the project was to charge a cell phone with the output. The electricity they generated was enough to light a small LED along with the charging of a mobile phone.

The following graph shows the delta temperature (in ^{o}F) vs. the output voltage generated using four (4) Peltier modules wired in series. Note in our battery design, the ΔT is 64 ^{o}C or 147.2 ^{o}F.

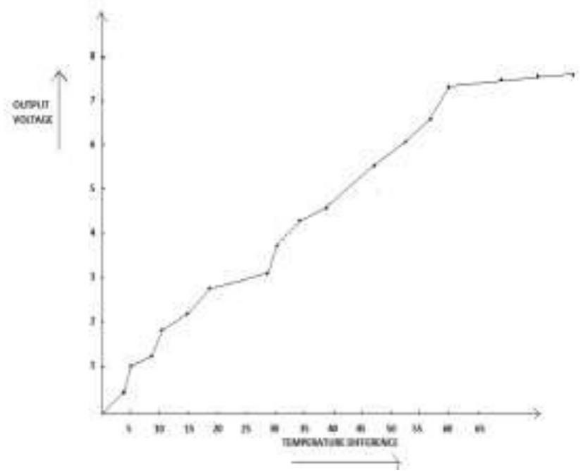

Figure 12: Difference in temperature vs. output voltage graph. Shows that the more delta temperature you have, the higher the voltage will be until a certain delta temperature

The expected output voltage, using the graph as an example, will be about 7.6VDC, as the Peltier modules peak at that voltage (about 2 VDC per module).

Figure 13.1: Output electricity should be able to charge a cell phone.

The thermoelectric generator should provide output similar to charge a cell phone via a voltage regulator (Figure 13.1). The project used a home-built voltage regulator, but I propose to use a commercially available regulator as they are inexpensive, prepackaged, and come with a USB plug (Figure 13.2).

A low-cost device to power the voltage converter is XINGYHENG DC-DC Buck Voltage Converter Power Module 4.5-40V 12V to 5V/2A + Power Supply Stabilizer Voltage Regulator with Voltmeter 5V USB Charger.

Figure 13.2: Voltage regulator (Amazon.com)

Expected Outcome – The expected outcome of the Phase 3 of Aim #2 is to construct a thermoelectric generator (TEG) that will generate enough output to charge a cell phone.

Potential Pitfalls and Alternative Strategies. – Although this phase of the project will succeed as we are modeling the TEG after a known study, it is possible the device will not perform as desired. If this is an issue, then I can look at the alternatives of:

1. Adding more Peltier modules to increase output.
2. Using a different type of Peltier module with higher efficiency for electric generation.

Specific Aim #3: Compare the model to the prototype to determine the predicted vs. actual performance of the system.

Once the system has been developed, measurements shall be taken to determine if the actual performance of the system matches the predicted performance. The following measurements will be taken–

- How much energy to “charge” the battery in watt hours.
- How long to “charge” the battery in minutes
- The temperatures in the hot and cold tanks during the charging cycle

- How much electrical energy is created during the discharge cycle, in watt hours
- The output voltage during the discharge cycle
- The effectiveness in charging a cell phone during the discharge cycle (observation only).

With these measured parameters, a calculation shall be done to determine the scalability of the device and how the device might be enlarged to power a portion of a home. A typical house in St. John's, Newfoundland energy (Iqbal, 2020) shows power consumption on a typical day, watts starting @ 5:00 pm (Figure 14).

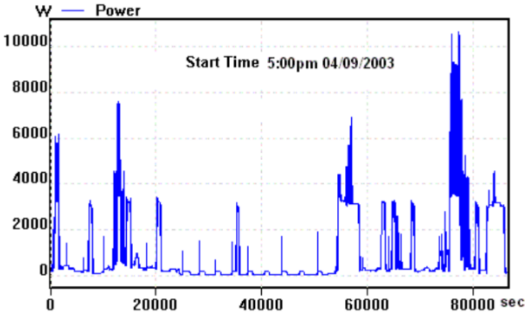

Figure 14: Power consumption of a home in a typical day in St. John's, Newfoundlnd. (Iqbal, 2020)

Expected Outcome – The expected outcome of the Aim #3 is to measure the performance of the prototype system using the speciifed parameter, and .extrapolate those measurements for a home system to determine how the device could be scaled to meet household requirements.

Potential Pitfalls and Alternative Strategies. – It is not expected to have any pitfalls at this point in the project as this is a straightforward measurement and extrapolation of the device

Section III: Resources/Equipment

The following is a preliminary listing of the resources and equipment planned to be used:

Item	Qty	Part	Description	Cost (EA)	Cost (Total)
1	2	Proshopping	150A RC Watt Meter, High Precision Power Analyzer, DC 0-60V Volt Amp Watt Checker Tester, with Digital LCD Screen-for Voltage(V) Current(A) Power(W) Charge(Ah) and Energy(Wh) Measurement	$22	$44
2	20	HiLetGo TEC1-12706	Semiconductor Refrigeration Tablets TEC1-12706 12V 6A Heatsink Thermoelectric Cooler Cooling Peltier Plate	$5	$100

			Module 40x40MM		
3	4	Noctua NF-A8 PWM	, Premium Quiet Fan, 4-Pin (80mm, Brown)	$17	$68
4	4	Awxlumv	Aluminum 80mm Heat Sink 3.15x3.15x1inch/ 80x80x27mm Heatsink Large Radiator Circuit Board Cooling Cooler 26 Fins for LED, Power High Fans - Sliver	$11	$44
5	1		12 VDC Power Supply 20 A	??	??
6	2	Weanos	Silver Metal Tin Box Lids - Large Containers, Holder for Keeping Car Keys, Cookie, Pencil Case, 8.2 x 4.7 x 2.4 inch	$15	$30
7	6	4X TEC1-12715	80 x 80 mm Large Water Cooling Block Aluminum Heatsink	$35	$210
8	1		CPU Water Pump, 12V DC 500L/H PC Water Cooling Pump G1/4 Thread CPU Cooling System Ultra Quiet Water Cooling Pump for Computer G1/4 Thread Water Pump for PC	$24	$24
9	1	ELGOO UNO	UNO Project Super Starter Kit with Tutorial and UNO R3 Compatible with Arduino IDE	$45	$45
10	4	HiLetGo	DC 3-5V MAX6675 Module + K Type Thermocouple Temperature Sensor Thermocouple Sensor Set M6 Screw for Arduino	$8	$32
11	1	DROK	Buck Converter 12v to 5v, DROK 5A USB Voltage Regulator DC 9V-36V Step Down to DC 5V-5.3V 5.2V 3.5-6A Volt Transformer Power Supply Module for Phone Fast Charging	$10	$10
12	1	TBD	Paraffin Wax – 1 Liter	TBD	TBD

Section V: Ethical Considerations

There are no specific ethical considerations. Materials used are benign and commonly available.

Section VI: Timeline

The timeline of the project follows:

Date	Activity
December 12,	Final Draft approved for testing

2023	
December 29, 2023	Completion of modeling and start material procurement
January 15, 2024	Completion of Phase 1 – Freeze Device
January 29, 2024	Completion of Phase 2 – Paraffin Melting Device
February 12, 2024	Completion of Phase 3 – TEG
February 26, 2024	Completion of Testing and Extrapolation of Data
March 5, 2024	Final report

Section VII: Appendix

Appendix I – Summary of Total Joules calculation for Water and Paraffin wax

	Water	**Paraffin**
Specific Heat	4.182 J/g (1)	2.5 J/g (1) (an average)
Latent heat of melting	334 J/g (1)	200 J/g (4) (an average)
Initial Temperature	20 °C	20 °C
Volume	1 Liter	1 Liter
Density	1.0 Kg/Liter (2)	0.93 Kg/Liter (2)
Mass	1 Liter x 1.0 liter/kg = 1 Kg	1 Liter x 0.9 liter/kg = 0.9 Kg (2)
Freezing Point	0 °C	64 °C (average, depends on type of wax) (3)
ΔT	20 °C – 0 °C = 20 °C	64 °C = 20 °C = 44 °C
Joules for temperature change	Mass x Specific Heat x ΔT = 1 kg x 4.182 J/g x 20°C = 83,640 J	Mass x Specific Heat x ΔT = 0.93 kg x 2500 J/kg x 404°C = 102,300 J j
Joules for Phase Change	Mass x Latent Heat of Melting = 1 kg x 334000 J/kg = 334000 J	Mass x Latent Heat of Melting = 0.93 kg x 339000 J/kg = 305100 J
Total Joules	83,640 + 417,600 = 417640 J	102300 J + 305100 J = 407400 J

Total Joules of both cold + hot water tanks is 417,640 J + 407400 J or **825,040 Joules**

ΔT of both tanks is 64 °C.

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Appendix 2 – Steps of calculations done to find the power and current needed to freeze 1 liter of water

Step 1 – Heat to be removed from water to bring water from 20 °C to 0 °C

$Q_1 = m \times C_p \times \Delta T = m \times C_p \times (T_1 - T_2)$

$Q_1 = 1.0\ kg \times 4182\ J/kg \times (20\ ^oC - 0\ ^oC) = 83{,}640\ J$

Step 2 – Latent heat to be removed to freeze water @ 0 ^{o}C

$Q_2 = H_g \times m$

$Q_2 = 334000\ J/kg \times 1kg = 334{,}000\ J$

Step 3 – The water is to be frozen within 10 hours (600 minutes), thus

Q : Heat Removal Rate

$Q = (Q_1 + Q_2)/time$

Q = (83640 J + 417600 J) / 600 = **696 Watts**

Step 4 – Calculate current at 24 VDC

Watts = Voltage * Current (for DC Circuits), so @ 24 VDC –

W = V * I, so I = W / V

I = 696 / 24 = **29 Amps**

Step 5 – **Calculate the number of TEC modules required**

696W (from Step 3) / 61 W per TEC Module = **11.4 modules**

Appendix 3 – Steps of calculations done to find the power and current needed to melt 1 liter of paraffin wax

Step 1 – **Heat to be added to paraffin to melt wax from 20 ^{o}C to 64 ^{o}C**

$Q_1 = m \times C_p \times \Delta T = m \times C_p \times (T_1 - T_2)$

$Q_1 = 0.93\ kg \times 2500\ J/kg \times (64\ ^oC - 20\ ^oC) = 102{,}300\ J$

Step 2 – Latent heat to added to melt paraffin @ 64 ^{o}C

$Q_2 = H_g \times m$

$Q_2 = 339000 \times 0.9kg = 305100\ J$

Step 3 – The paraffin is to be melted within 10 hours (600 minutes), thus

Q : Heat Removal Rate

Q = (Q_1 + Q_2)/time

Q = (102300 J + 305100 J) / 600 minutes = **509 Watts**

Step 4 – Calculate current at 24 VDC

Watts = Voltage * Current (for DC Circuits), so @ 24 VDC –

W = V * I, so I = W / V

I = 508 / 24 = **21.2 Amps**

Section VIII: References

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