FAMU-FSU College of Engineering

Department of Electrical and Computer Engineering

Solar Thermal Generator

Team #14

Final Report

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Abstract

Team 14's project manager, Ernest Crabtree, proposed the solar thermal generator project to The Department of Electrical & Computer Engineering at the FAMU-FSU College of Engineering. The objective of the solar thermal generator project was to design a device that would provide a portable source of sustainable energy for use in remote areas. The generation of power would be achieved by means of thermo-electric generators operating on the Seebeck principle of dissimilar metal junctions.

Ideally, the effective design must be simple to use for your average consumer. The system should run autonomously at the push of a button to intelligently track the sun, mechanically align itself and charge electric devices as well as the provided battery.

This report will outline what has been accomplished and the research and the final design that has been developed along with future goals and improvements that can be made.

1 Introduction

Currently, there is no effective and simple way to generate power in remote locations, such as campsites and national parks. In order to supply power to everyday electronic devices a gas generator is traditionally used. However, due to their tremendous weight, noise factor, and environmental impact, it has become increasingly problematic to use these generators responsibly in isolated locations.

While portable photovoltaic technology is viewed as the current solution to this dilemma, it is important to recognize that there exist more promising alternatives, specifically in solar-thermal technology. Currently, photovoltaic cells are only able to harness specific wavelengths within the spectrum of visible light to generate power. Additionally, if the sun were obscured by the geographic location or weather conditions, a photovoltaic cell would be unable to produce any energy. However, thermo-electric generators possess the capability to utilize the heat from the entire spectrum of visible light as well as UVA, UVB, and infrared rays. This allows the process of thermo-electric power generation to continue even while the sun is out of sight.

The overall goal for this project is to develop a convenient and portable device that transforms solar thermal energy into usable electricity. In order to for the device to be applicable as a charging station, it would be required to generate twenty watts of electricity. Other features include a convenient assembly and disassembly process as well as minimal environmental impact. The product has a wide scope and numerous possible applications in the commercial world.

1.1 Project Scope

The overall undertaking of the Solar Thermal Generator project required knowledge within the fields of energy storage, voltage regulation, mechatronics, and computer programming. The following is a succinct list of the expected scope of the project.

- Solar thermal heat collection
- Solar tracking program and algorithm
- Two axis mounting system
- TEG cooling or heat dissipation
- Energy storage and power output
- Scalability
- Portability

1.2 Needs Assessment

At the crux of this project, the simple problem we wish to address is this: people in remote locations do not have access to easily obtainable, inexpensive electricity for powering their electrical devices. Our proposed Solution is to provide electricity in remote locations using solar radiation, arguably the most abundant form of renewable energy on earth. Using a TEG installed in a mechanism for tracking the relative position of the sun and effectively storing energy will provide average consumers with a means of power generation in an environmentally safe way.

No.	***Needs***	***Wants***
1.	*Generate 20W of power*	*Portability*
2.	*Energy storage & efficiency*	*Low cost*
3.	*Solar tracking*	*User friendly*
4.	*Shock resistant*	*GPS modulator*

Table 1: Needs and Wants

1.3 Project Constraints

To meet the specific needs illustrated above, the following limitations and constraints are addressed as follows

- Device weight must not exceed 50lbs
- The device itself must be compact (ideally less than 3ft^{3})
- The device should be resistant to corrosion and be waterproof
- Must operate in the confines of the designated budget
- Meet with all applicable safety and consumer standards
- Provide maximum standby time

2 Design Requirements and Specifications

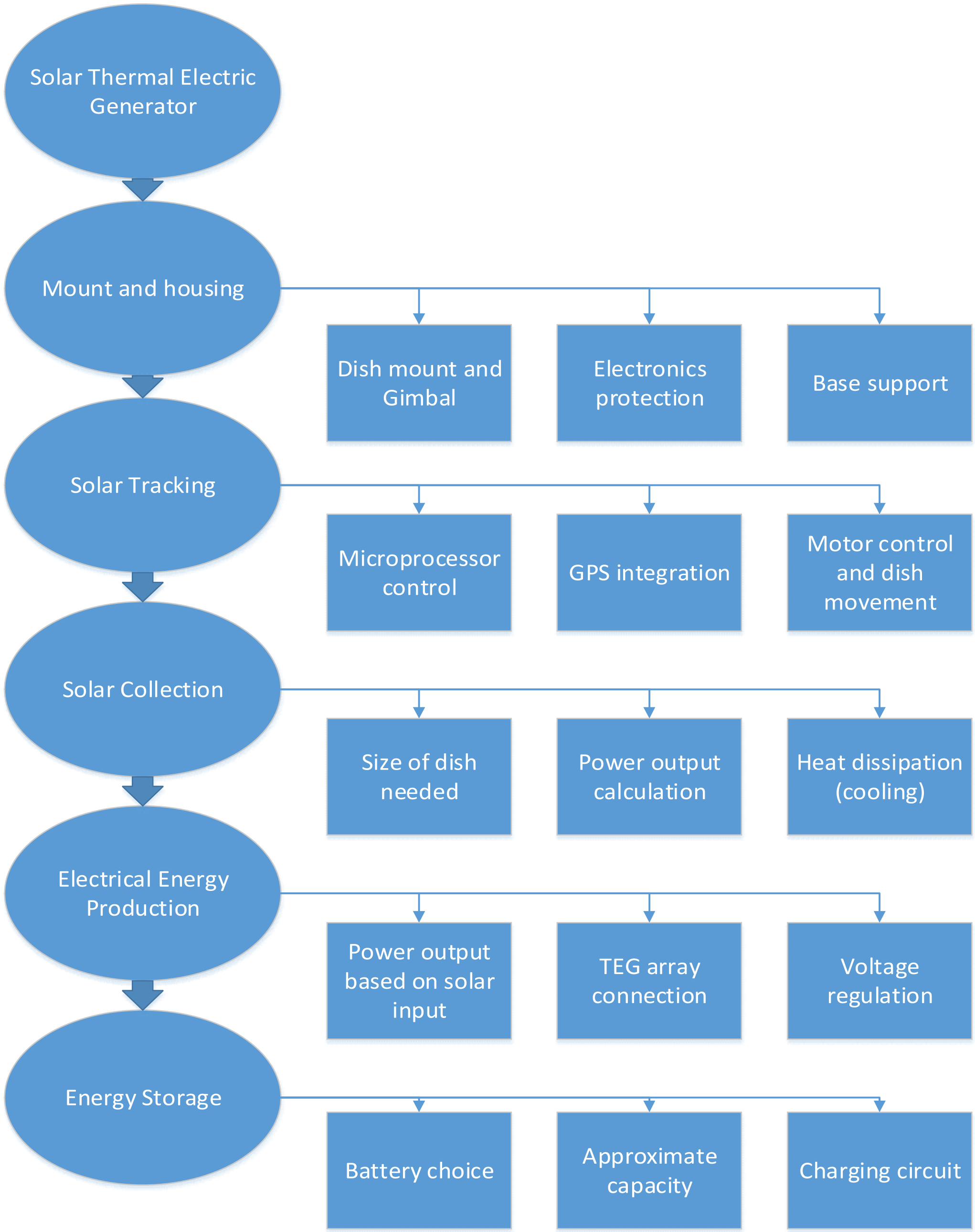

Figure 1: Design Overview

2.1 Solar Tracking

To show in detail the two-axis tracking mechanism of the prototype, it can be useful to have a close look to the linear actuator and stepper motor included. In relation to the first one, as Figure 1 shows, the linear actuator is responsible for the tilt movement of the tracker, since it has an axial rod with a tiny but powerful internal gearbox and a rectangular section to increase its rigidity. Its working principle consists in pulling or pushing a certain load (solar collectors in this case) throughout the length of the rod. The speed of displacement depends on the gearbox mentioned before and the stepper motor settings.

Figure 2: Two-axis Mount for Solar Tracking

For solar tracking the NREL's solar position algorithm is used to track the sun. The algorithm required too much dynamic (heap) memory than anticipated which was then switched to a smaller and slightly less efficient algorithm provided by the Institute of Earth Science. During testing phase, the results were matched against those calculated from the Earth System Research Laboratory. The output was very much similar and just slightly off by only tenth of a degree as shown in the table below.

Output	Solar Tracking Algorithm	Earth System Research Laboratory
Zenith	50.1645 [degrees]	49.68 [degrees]
Azimuth	160.99 [degrees]	160.76 [degrees]

Table 2: Comparison of Solar Tracking Algorithm

The Solar Tracking control chart below shows that the readings from compass module and GPS module will be fed to the microcontroller, which then using the SPA algorithm perform operations of calculating the Azimuth and Zenith angles depending on the time and location.

After getting all the desired inputs and performing necessary operations the controller will then move the dish accordingly.

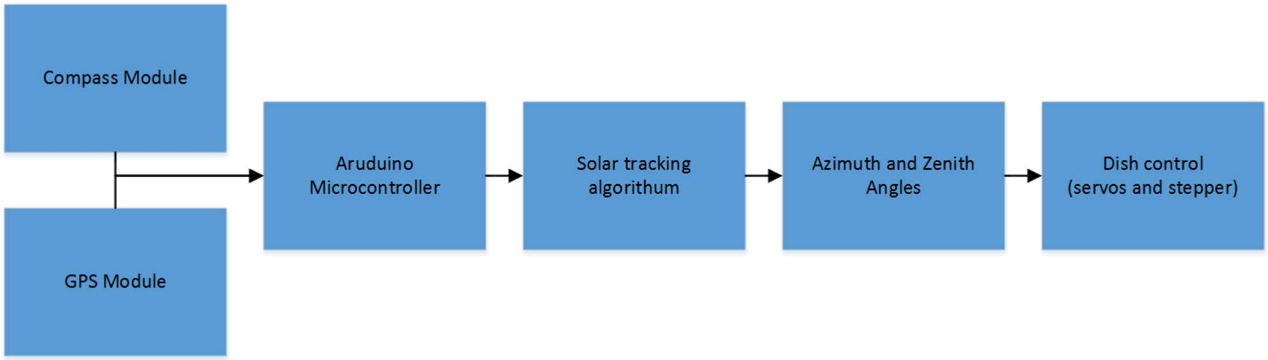

Figure 3: Solar Tracking Flow Diagram

2.2 Solar collection

The information from the National Renewable Energy Lab (NREL) shows that the average radiated solar power in our area is approximately 1000 W/m^2. From the equation for the surface of a paraboloid the dish was found to be 0.36 m^2. This would indicate that the dish has the ability to collect 36% of that radiated power, or 360 W. That figure represents a dish and angle that is 100% efficient, and is idealized. The actual power that the dish collects will be determined by experimental data.

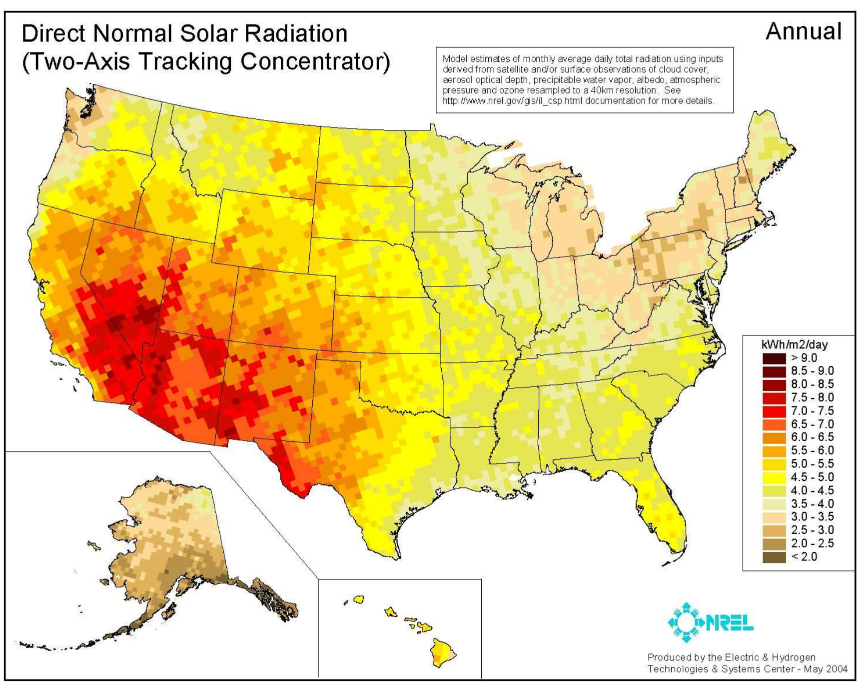

Figure 4: Example Solar Irradiation Map

2.3 Electrical Energy Production

2.3.1 TEG estimated outputs and modeling

In this section, the ideal cases for the TEGs will be discussed and the possible combination arrays will be discussed. We will expect the TEGs to follow the standard Seebeck equation and will model the circuits as voltage sources with a small internal resistance.

Equations and related information for circuit modeling

$$J = \sigma(-\nabla V - S\nabla T)$$

With an open circuit we can assume that:

$$J = 0$$

We can also assume that the voltage and temperature both vary in only one direction:

$$\nabla V = \frac{dV}{dx} \quad \nabla T = \frac{dT}{dx}$$

Now, putting them all together, the following equation is provided.

$$dV = -SdT$$

Now we can define the voltage across the Ideal TEG:

$$V = S\Delta T$$

Since this newly derived equation assumes that there is no internal resistance, we will have to add some to our model circuit. The internal resistance of the TEG is given in the datasheet. See **Error! Reference source not found.**.

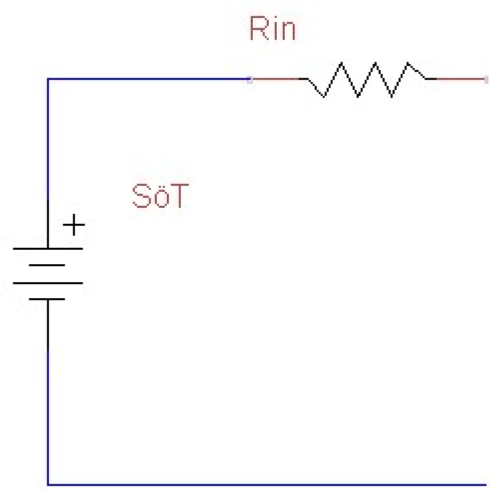

Figure 5: Circuit 1

For Max power transfer we need to match the input resistance. We can find the maximum power will be given by the following.

$$P_{max} = \frac{(S\Delta T)^2}{4R_{in}}$$

If the TEGs are connected in parallel, we can find the equivalent circuit for n number of chips.

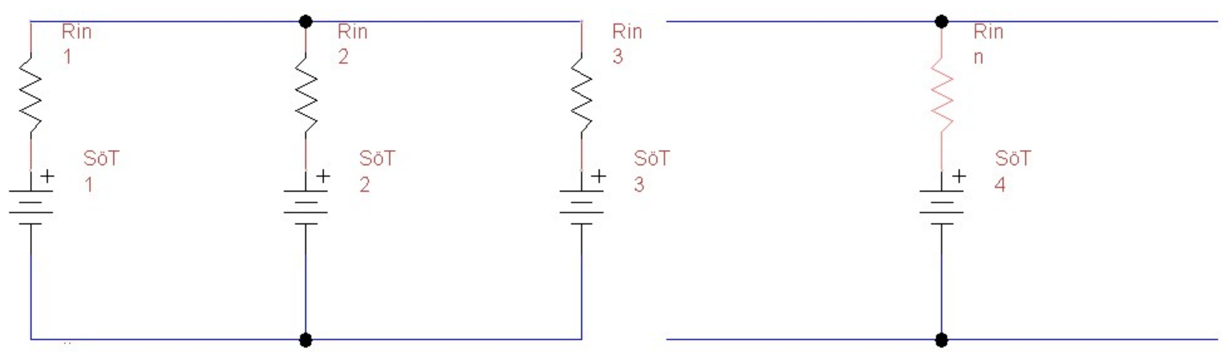

Figure 6: Circuit 2

We can now find the Thevenin equivalent of the parallel circuit:

$$V_{oc} = S\Delta T$$

$$R_{th} = \frac{R_{in}}{n}$$

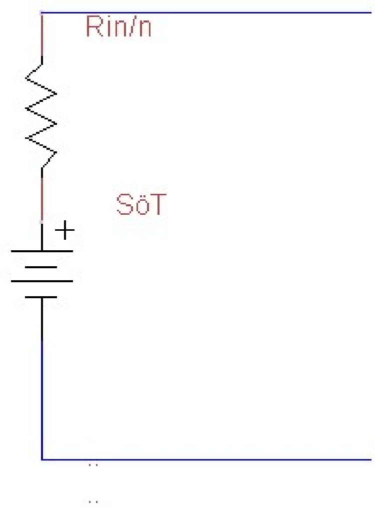

Figure 7: Circuit 3

We can now do the same for the series configuration.

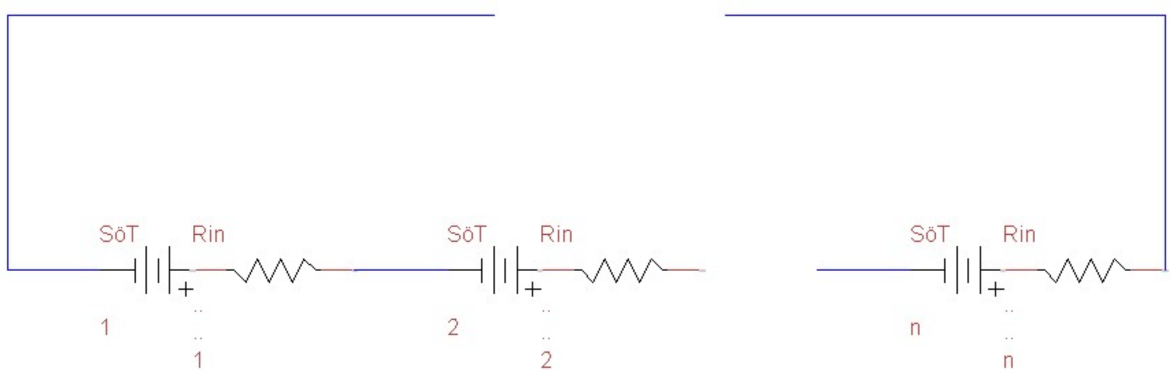

Figure 8: Circuit 4

$$V_{oc} = nS\Delta T$$

$$R_{th} = nR_{in}$$

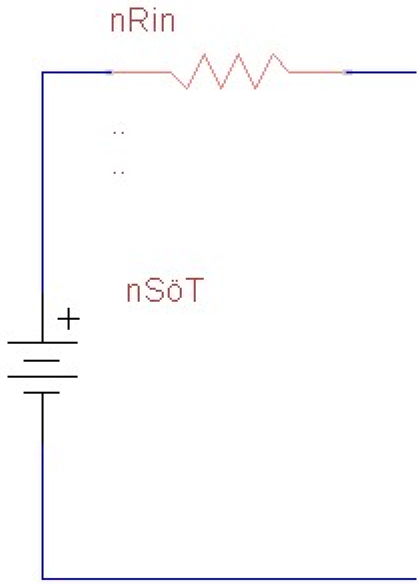

Figure 9: Circuit 5

Because of the conservation of energy, the chips will not produce any more or less power depending on the series or parallel arrangements. It can be determined that the maximum power transfer of the chips will be:

$$P_{max} = \frac{n(S\Delta T)^2}{4R_{in}}$$

Maximum power transfer requires that the load match the internal resistance of the chip.

2.3.2 Voltage regulation with boost converter

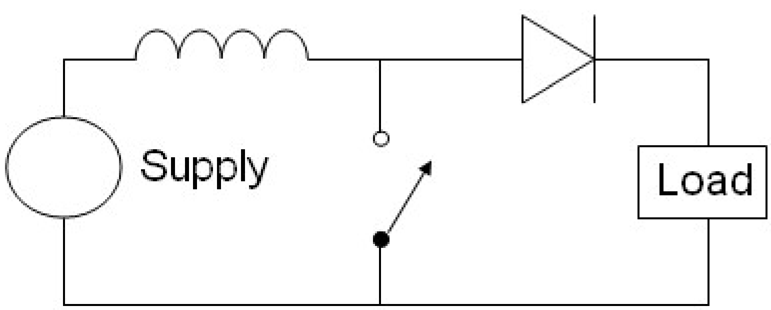

Figure 10: Boost Converter Circuit

A boost converter is pictured in **Error! Reference source not found.**. The switch is usually a high current capable MOSFET with a square wave controlling it.

Ideal boost converter can step voltage up according to the following equation.

$$V_{out} = \frac{V_{in}}{1 - D}$$

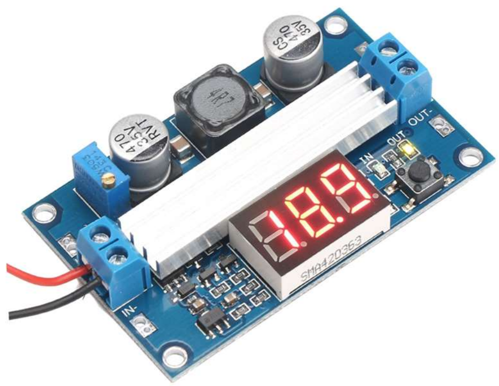

Figure 11: Boost Converter

In the equation, D is the duty cycle of the PWM that will control the MOSFET switch. In order to complete the circuit, a microcontroller will be needed to keep the voltage regulated and adjust the PWM as more load or less load is added. This equation does not work when a load is attached.

More accurate equations for finding the values for the inductor, capacitors and D needed are shown below and are more deeply explained in the report published by TI.

$$V_{out} = \frac{\eta V_{in}}{1 - D}$$

η is the efficiency of the boost converter.

$$C_{out} = \frac{\frac{V_{out}}{R_{min}} * D}{f_s \Delta V_{out}}$$

Where f_s is the switching frequency of the MOSFET and ΔV_{out} is the maximum allowable ripple on the output.

R_{min} is the maximum load that can be given to the output of the boost converter. For our specific application it can be estimated by the flowing equation. This R_{min} value will allow for maximum power transfer.

$$R_{min} = \frac{R_{in}V_{out}}{\eta V_{in}}$$

The value of the Inductor can be given by the following equation.

$$L = \frac{V_{in}(V_{out} - V_{in})}{\Delta I_L f_s V_{out}}$$

$$\Delta I_L = .3 * \frac{V_{out}}{R_{min}} * \frac{V_{out}}{V_{in}}$$

A regulation circuit will be needed in order to keep the output stable no matter the load or go into protection mode if there is a fault or the load is too heavy.

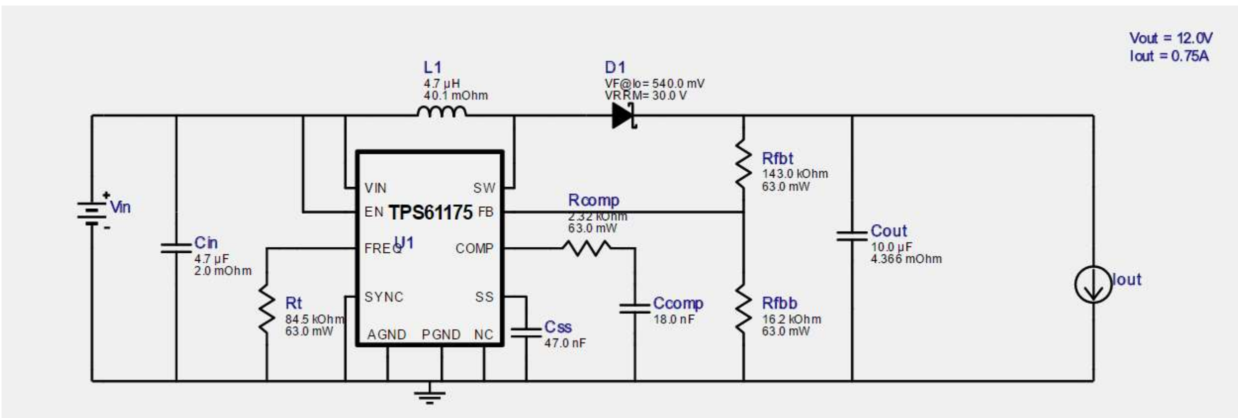

Figure 12: Possible Converter Circuit

Error! Reference source not found. shows a possible circuit using the Texas Instruments TPS61175. The circuit above can deliver P_{max} = 9W. More than one of these circuits could be used or along with the 5V output. Different chips with higher output are also available.

The LT1619 from Linear technologies can produce a 5V output with 8A and 12V output with up to 5A. It is also being considered for the application. Multiple chips will most likely be purchased and tested. The 12V circuit using the LT1619 is shown in **Error! Reference source not found.**.

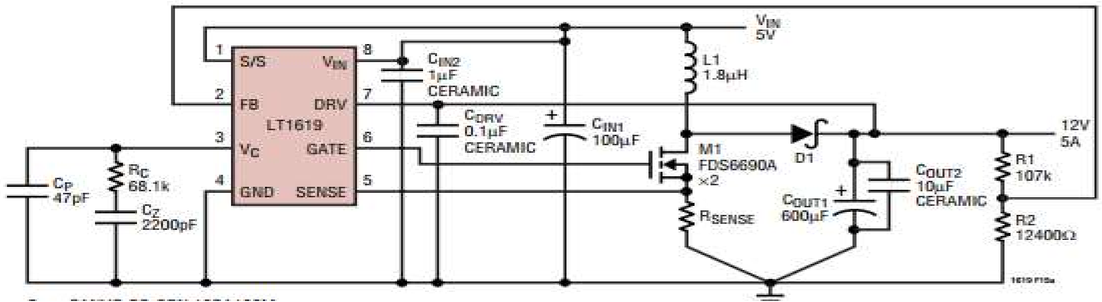

Figure 13: Another Possible Converter Circuit

2.4 Energy Storage

2.4.1 Overview

A main feature within the design of our Solar Thermal Generator will be its ability to function as a source of energy even when the device is not directly collecting energy from the sun. This feature is important within our design because it will allow our generator to be functional throughout all times of day. This feature will require our design to incorporate an energy storage application using Nickel Metal Hydride batteries.

2.4.2 Battery Features

The students concentrated on two battery types to implement their energy storage applications, Nickel Metal Hydride and Lithium Ion. Although the Lithium Ion battery offers slightly improved characteristics compared to the Nickel Metal Hydride batteries, the students decided to implement the Nickel Metal Hydride application due to lower costs as well as improved safety during operation. A comparison of each application's pros and cons can be seen in the tables below.

Nickel Metal Hydride Battery	
Pros	**Cons**
Cheap ($34 for 12 count pack)	Heavy
Can be recharged and reused 150-500+ times	Lose power when sitting idle (1% per day) Need to be recharged and used every 1-2 months
Steady and lasting discharge	Begin to hold charges for shorter periods late in their life cycle
Delivers energy capacity at a more constant rate (flatter discharge rate)	Should not be stored in warm areas (affects longevity)
Much safer than Lithium. Environmentally friendly.	Must be charged before first use
Recyclable	Suffer from memory effect.
Low internal impedance	Low operating voltage (1.2 V)
Can tolerate overcharge and over discharge due to safety vents that depressurize cell	
Rapid Charge possible in 1 hour	

Table 3: NiMH Battery Specs

Lithium Ion Battery

Pros	Cons
Low discharge rate (retain charges longer than any other battery)	Loses energy capacity with time (even if not used)
High energy density (stores more energy in a smaller and lighter battery)	Expensive ($4-$20 per battery)
500-1000+ number of recharging cycles	Dangerous. Overcharge may result in cell rupture.
High cell voltage (3.6 V-3.7 V)	High voltage capacity can make the battery too powerful for some devices and can damage circuitry
	Require battery management system

Table 4: NiHM Batery Specs 2

2.4.3 Battery Charger

The students primary approach in regards to battery charging was to design and construct their own circuit to charge the Nickel Metal Hydride cells. After extended research into the topic, the students realized the complexity and sheer size that their charging circuit would be. One of the student's main goal is to maintain portability with their device; due to this the students realized that it would not be practical to construct their own circuit due to the unnecessary space that the circuit would consume. The student's found a better solution to their problem of charging their battery cells by implementing the BQ24401 chip manufactured by Texas Instruments. The BQ24401 chip is a low price 8 pin chip that's primary function is the fast charge of Nickel Metal Hydride battery packs. The BQ24401 chip is a configurable, monolithic integrated circuit that utilizes three parameters that can be preset by the user to charge the batteries by monitoring battery voltage as well as battery temperature. Some of the primary features of this chip include but are not limited to safe management of fast charge for Nickel Metal Hydride battery packs, pre-charge qualification for detecting shorted, damaged, or overheated cells, fast charge termination by monitoring temperature differential, maximum temperature, and maximum charge time, as well as a sleep mode for low power consumption. The BQ24401 chip prevents the cells from overcharging by monitoring cell voltage, cell temperature, or both. The image below shows how the chip monitors these parameters with respect to time to determine when the cells are at full charge.

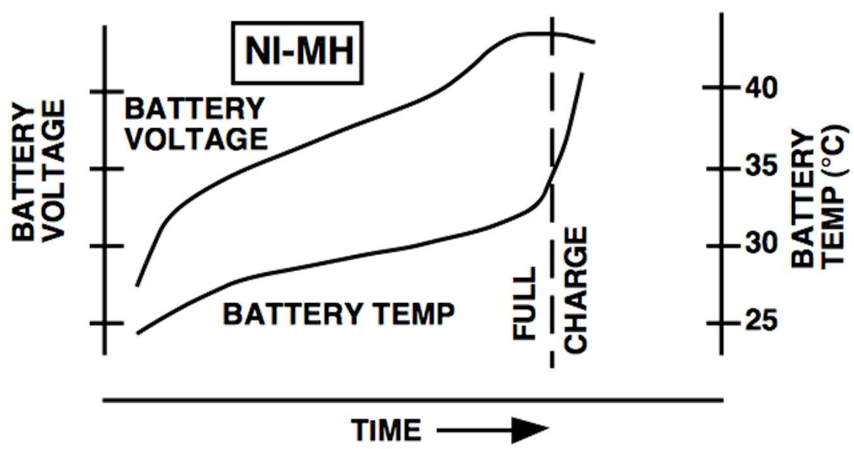

Figure 14: NiHM Charge Graph

2.4.4 Battery Test and Verification

The students were able to test a Nickel Metal Hydride battery using a battery analyzer to cycle the battery and receive data for various parameters including charge and discharge capacity and energy, as well as energy density and charge/discharge efficiency. The graph below shows the waveforms of the battery voltage and current through several cycles of charge and discharge.

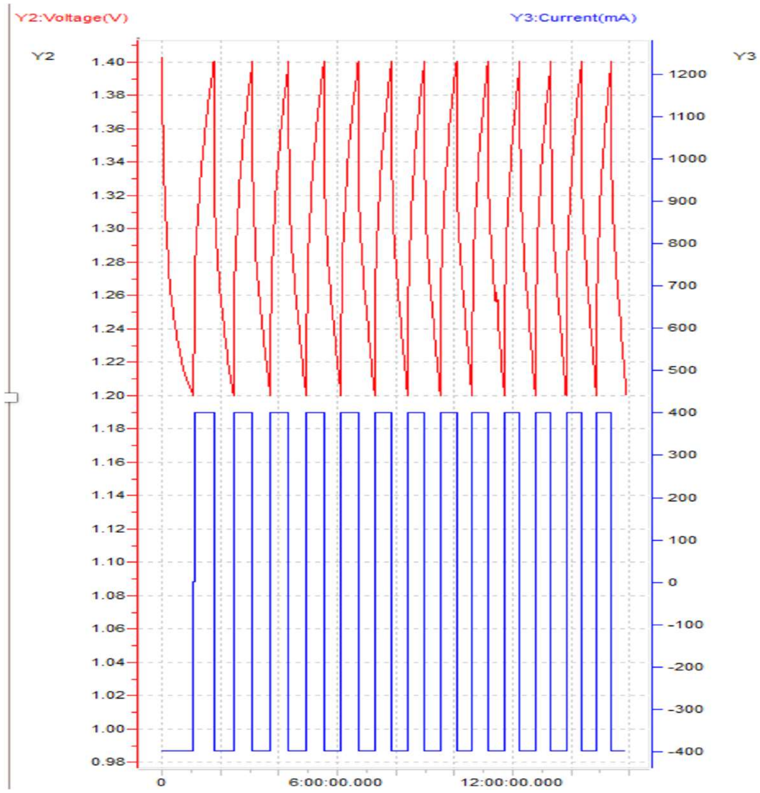

Figure 15: NiHM Test Cycles

From this graph, you can see that the battery was charged to a maximum voltage of 1.4 V and a maximum current of 1.2 A. Below is a table that represents the data received from the cycling of the Nickel Metal Hydride battery.

Experimental Results (last few cycles)					
Cycle	Cap_Chg(mAh)	Cap_DChg(mAh)	Charge/Discharge Efficiency (%)	Engy_Chg(mWh)	Engy_DChg(mWh)
11	212.3	212	99.843	285.4	266.6
12	209.7	209.5	99.894	281.9	263.6
13	207.2	206.7	99.786	278.5	260.1
Average :	209.7	209.4	99.841	281.9	263.4

Table 5: NiHM Experimental Results

Due to the fact that the student's cycled the battery at its maximum current rating, the data they received was quite flawed. The energy density was much lower than the expected 70 Wh/kg while the charge/discharge efficiency was higher than the expected 80-85 percent.

2.4.5 Energy Storage Summary

In conclusion, the students found through various research and experimentation that even though the Nickel Metal Hydride does not boast the most impressive characteristics compared to other energy storage applications, it is the best solution to implement into their specific design. The students believe that the Nickel Metal Hydride battery will offer lower cost while improving safe operation as well as offer a dependable and exceptional lifetime within their design. Due to all of these factors, the Nickel Metal Hydride battery offers the best solution to their specific problem and design to create a functional and dependable energy storage application that will allow for furthered operation throughout all times of day.

2.5 Design Implementation and Control

The data collected from the experimental setup is used to calibrate and validate the testing efforts and improve optimization. The second and most important aspect of the testing phase is designing and implementing controls. The design control will be operated by a microcontroller that implements the control system of the device.

The microcontroller used in our senior design project was Arduino Mega over the choice of TI-MSP430 due to some design limitations and due to the user-friendly nature of Arduino. The design stage then maps the components and passes the control to the system accordingly. The earlier mentioned modules and functionality of the unit is controlled by the programmable logic controller that process the inputs received by the modules such as Voltage regulator, Solar tracking, and Temperature control process the request and send it out to the appropriate output. The schematic shown below gives a better understanding of control process.

Figure 16: Arduino Mega

The diagram above shows that after receiving inputs from the voltage and GPS modules, the controller will process the data and perform necessary operations to deliver the control to the output modules in our case, to servos motor for elevation of the dish mount or to the charge indicator to provide visual indication of battery charging once the generated power output exceeds the power consumption limit.

2.6 Experimental Testing for Heat Transfer

These experiments were used to gain a better understanding of the potential output from the TEGS. While the final chips that will used for this project are not purchased yet, the TEC-12706 has been obtained for experimentation.

In addition to learning about the TEGs, these experiments were used to test the ability of various heatsinks to dissipate heat. By performing these tests we will be able to determine if we can utilize one of these heatsink designs in our final design or if we should pursue an alternative cooling technique such as water cooling utilizing the principle of a thermosiphon.

2.6.1 Experiment 1- Procedure and Results

Three TEGs were connected in series and mounted between two rectangular aluminum plates with thermal paste. The hot side of the chips was placed over a single tea candle with an average heat output of 25 W. Heatsinks were mounted on top of the system with thermal paste. For the first set of tests, an aluminum fin-style non-heatpipe design was used. For the second set of tests, an aluminum fin-style heatpipe design was used. Measurements for voltage were taken over varying periods dependent on when the system reached saturation. We attempted to read the corresponding temperatures for the hot and cold side of the chip in order to calculate the internal resistance and Seebeck coefficient. However, we found our non-contact infrared thermometer to be faulty and our temperature readings to be unreliable.

Calculated Internal Resistance	Temperature of cold side aluminum plate	Temperature of hot side aluminum plate	Voltage Output no heat source
6 [Ω]	23.1 [C]	23.1[C]	0.5 [V]

Table 6: Experiment 1 Initial Measurements

Output Voltage[V]	Runtime [min:sec]
0.5	0:00
0.6	0:05
0.7	0:20
0.8	0:40
0.9	1:00
1.0	1:20
1.1	1:40
1.2	2:00
1.3	2:25
1.4	3:03
1.5	3:53
1.6	4:53

Table 7: Output of Test Chip

Peak Voltage [V]	Saturation Voltage [V]
1.63	1.1

Table 8: Non-Heatpipe Design

Output Voltage [V]	Runtime [min:sec]
0.2	0:00
.3	0:07
.4	0:11

.5	0:17
.6	0:24
.7	0:32
.8	0:41
.9	0:51
1.0	1:03
1.1	1:20
1.2	1:37
1.3	1:55
1.4	2:24
1.5	2:50
1.6	3:30
1.65	4:20
1.68	5:00
1.7	5:08
1.77	13:00
1.56	16:00
1.54	19:00
1.52	21:00
1.48	23:00
1.47	24:00
1.44	25:00

Table 9: Output of Test Chip

Peak Voltage [V]	Saturation Voltage [V]
1.77	1.4

Table 10: Heatpipe Design

The results of this set of tests have limited usefulness due to the lack of temperature readings. However, we were able to observe the ability of various heatsinks to dissipate heat. We found both the heatpipe and non-heatpipe design to be inadequate based on the maximum output voltage and the output voltage after the system reached a constant temperature differential (i.e. saturation). It is obvious based on these experiments that an alternate means of dissipating heat is required such as water-cooling or some combination of a water-cooling design and heatsinks.

2.6.2 Experiment 2: Procedure and Results

The chips were placed between two pieces of aluminum with holes drilled for thermometers to be inserted close to the center. The hot side of the chip was placed over a tea candle in order to receive heat. The cold side facing up and the heatsink was attached. Thermal paste was used between the chip and the aluminum and between the heatsink and the aluminum on the cold side.

The voltage was measured along with the temperatures of each side of the chip. Once thermal equilibrium was reached and the chip Voltage stabilized, a test was performed in order to compute the internal resistance of the chip. Next, the Seebeck coefficient was computed. These results were compared to theoretical values found online and in the datasheet for the chip.

T_{hot} (K)	T_{cold} (K)	ΔT (K)	V_{oc} (V)
306.3	301.8	4.5	.2
311.3	301.9	9.4	.4
316.9	302.4	14.5	.6
322.9	303.5	19.4	.8
330.7	306.7	24	1
337.6	312.0	25.6	1.06

Table 11: Experiment 2 Results

After the chip had time to stabilize and the temperatures were staying constant, a 5Ω load was attached and the voltage across the load was found to be .38V. Using the following equations, the internal resistance was found as well as the maximum power that could be delivered.

$$I = \frac{.38V}{5\Omega} = .076A$$

$$R_{in} = \frac{1.06 - .38V}{.076A} = 9\Omega$$

$$P_{max} = \frac{V_{oc}}{4R_{in}} = \frac{1.06V}{4(9\Omega)} = 29mW$$

According to the datasheet for the TEC-12706, the internal resistance is 2Ω. This value is not constant and can be affected by the temperature of the chip. The closer the hot side gets to its maximum allowed temperature, the higher then internal resistance becomes.

The Seebeck coefficient can now be calculated.

$$S = \frac{V}{\Delta T} = \frac{1.06V}{25.6K} = 41\, {}^{mV}\!/_{K}$$

According to multiple researchers online, the Seebeck coefficient for this chip can be expected to be closer to 50mV/K. Again, the coefficient is actually dependent of temperature so as the hot side gets closer to the threshold, the coefficient drops and the efficiency of the chip is impacted.

3 Operations Manual

3.1 Introduction

This project is an entrepreneurial-based undertaking sponsored by FAMU-FSU College of Engineering, specifically through Dr. Michael D. Devine. Currently, there is no effective and simple way to generate power in remote locations, such as campsites and national parks. In order to supply power to everyday electronic devices a gas generator is traditionally used. However, due to their tremendous weight, noise factor, and environmental impact, it has become increasingly problematic to use these generators responsibly in isolated locations.

While portable photo-voltaic technology is viewed as the current solution to this dilemma, it is important to recognize that there exist more promising alternatives, specifically in solar-thermal technology. Currently, photo-voltaic cells are only able to harness specific wavelengths within the spectrum of visible light to generate power. Additionally, if the sun is obscured by the geographic location or weather conditions, a photo voltaic cell would be unable to produce any energy. However, thermoelectric generators possess the capability to utilize the heat from the entire spectrum of visible light as well as UVA, UVB, and infrared rays. This allows the process of thermal-electric power generation to continue even while the sun is not in full radiation.

The overall goal for this project is to develop a convenient and portable device that transforms solar thermal energy into usable electricity. In order for the device to be applicable as a charging station, it would be required to generate 20W of electricity. Other features include a convenient assembly and disassembly process as well as a low environmental impact.

The basic idea for this project was conceived for the sole purpose of being able to generate electricity for the myriad of electronic devices used by an average outdoorsman aiming to be environmentally responsible. Currently, there is no effective and simple way to generate power in remote locations, such as campsites and national parks. In order to supply power to everyday electronic devices a gas generator is traditionally used. However, due to their tremendous weight, noise factor, and environmental impact, it has become increasingly problematic to use these generators responsibly in isolated locations. Although photo voltaic cells were initially considered for the design, a more interesting process involving thermoelectric power generation was sought as the more promising solution. The concept transformed further with a trivial amount of experimentation using a small parabolic dish to concentrate the heat provided by the sun to a fixed point. The system should run autonomously at the push of a button to intelligently track the sun that will mechanically align itself and charge electronic devices as well as the provided battery. The finished product is ideally portable and will be used as light and heater applications in a relatively remote location where a power grid is unavailable or unreliable. Ideally, the effective design must be simple to use for your average consumer.

3.2 Warnings and Safety Regulations

⚠ WARNING: DEVICE IS OPERATED AT HIGH TEMPERATURES. RISK OF BURNING AND LOSS OF VISION/EYE DAMAGE CAN OCCUR IF OPERATED IMPROPERLY. INORDER TO AVOID PHYSICAL HARM, PLEASE FOLLOW THE FOLLOWING SAFETY GUIDELINES.

Safety Equipment

1. Tinted safety goggles.
2. Heavy duty work gloves or thermal protective gloves
3. Long sleeves and closed toed shoes

Safety Procedure

1. Before handling or operating device, put on tinted protective eyewear and heavy duty work gloves.
2. Do not look directly at the focal point of the dish or directly into reflective surfaces when the dish is in sunlight. Focused rays from the dish and reflectors can cause severe eye damage and may cause temporary or permanent blindness.
3. During setup, operation and general handling, do not allow any exposed skin to make contact with device components. Device is operated at high temperatures and contact can result in severe burns.

3.3 Components

The project has the following major components:

- Parabolic Dish
- Dish mount
- Thermal Electric generator
- Heatsink
- Radiator
- Boost Converter
- Arduino
- Stepper motors and servos for dish control
- Battery charger and NiMH battery cells
- Project box and base
  Note: The internal components of the base are depicted in Figure 1

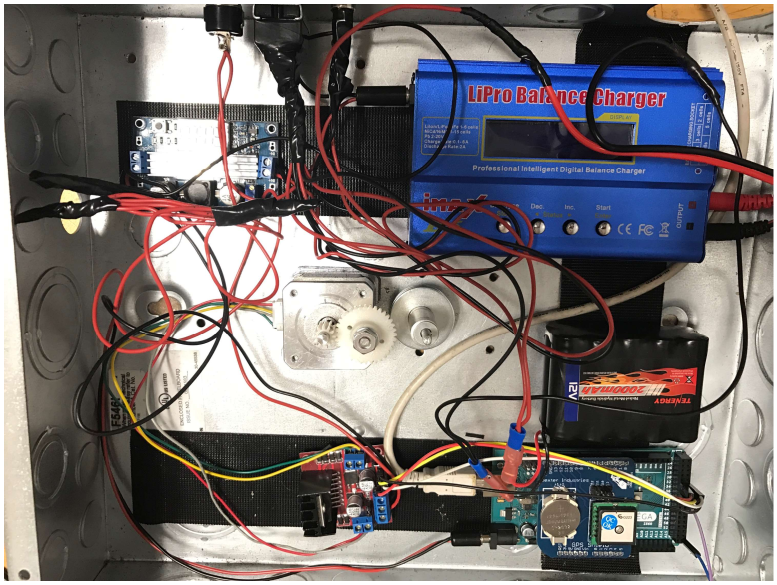

Figure 17: Electrical Components in Base

The component most likely to fail is the dish mount. The mount was handmade and if it were to fail it would be beneficial to have a mechanical engineer design a suitable replacement. If another group takes over this project, that may be the first thing we would recommend investing time into.

The TEG has a very specific temperature range that it is effective in. if it overheats on the cool side, it will not produce the energy that is required. If the cooling system fails, it will need to be replaced with new water, new hoses and in the future a fan may be helpful in removing more heat form the chips.

The battery will also need to be replaced if the cells fail. This will be due to normal wear. Nickel Metal Hydride batteries were chosen for this design due to their functionality and range of safe operation.

The rest of the components are relatively reliable and the code will be provided from the Arduino so if that needs to be replaced it can be recoded and implemented. The entire system is meant to be modular so that components can be easily replaced if necessary.

3.4 Initial Setup

In order to set up the device the user will have to reset the dish to the starting position (arrows must line up from dish to base) and the dish must be in its fully downright position.

1. Manually point dish if necessary with power off (it should be able to reset with the button on the top but if power is lost at any point, this will not work properly)

2. Point entire device south (do not only turn the dish) using the compass onboard
3. Be sure the switch is off for battery charging
4. Turn the device on to use the battery as the source – the dish should automatically adjust to point towards the sun

3.5 Operation

In theory, the operation of the device should be automatic but due to time constraints and many mechanical issues that were involved, the device is not automatic. It requires the user to manually change the power source (battery or TEG) and also requires that the user switch the power supply when appropriate. If the dish only functions from the battery, it will eventually die and never use the energy the TEG is collecting. When the time is appropriate, the device must be switched to use the TEG as the source for electricity. The procedure is as follows:

1. Hold down the hold button
2. Flip the power switch from battery to external
3. According to user preference and energy being collected, the battery charger can now be enabled and charging can begin
   Note: The aforementioned buttons and switches are depicted and described in Figure 2

Figure 18: External Switches

The power input from the TEG's is located on the far left of the base. The red switch located in the middle of the box is the power supply in which the up position supplies power from the external source while the down position supplies power from the battery source. The switch on the far right of the base is the power supply for the battery charger. The up position of this switch turns the battery charger on while the down position of the switch turns the battery charger off.

It should be noted that the device is set to trickle charge the battery at 1/8C so it will take approximately 5-7 hours to charge the battery depending on how much it must be charged. Also, the battery is not regulated so deep discharge cycles can occur if caution is not taken. When the device is using the battery as the source, the boost converter will attempt to boost the output until the battery voltage drops below ~4V (very deep discharge).

3.6 Troubleshooting

Some minor problems that may occur and their solutions are as follows:

- The battery has completely died
  If the battery completely dies, there is a good chance that it will be damaged from deep cycling. To attempt to charge the battery, external supply can be given (through the dish input plug on the device between 5-12V) and the device can be turned on to use external supply (red switch) and the batteries can be charged. If the cells are badly damaged, the battery can be replaced with a suitable replacement.
- The dish is not pointing the correct direction
  Turn the device off (red switch to middle position) and manually reset the dish by lining up the arrows on the base and the dish. Also, be sure the dish is in its fully downright position. External power may need to be supplied if the battery has completely died (See battery died). Repoint the device south. With external power supplied if necessary, turn the device back on to use either the battery or external supply.
- The device has stopped responding
  Try the reset procedure. It is as follows
  1. Try using the reset button, then turn the power button off.
  2. Follow the setup procedure
  3. Turn device back on to use battery as source then switch the source as outlined in the Operation section

More advanced problems may occur.

As stated in the components section, the mechanical design is flawed in many ways. If this project is being taken on by future students, a great effort should be invested in redesigning the dish control, gearing, and mount. This project could greatly benefit from the addition of a mechanical engineer.

There is a good chance the single TEG employed will not supply enough power. This may be fixed by adding an additional TEG, using a more polished dish, and/or improving heat dissipation. In order to complete proof of concept procedures, an external supply was used for most of the demonstrations or was used to charge the batteries then the batteries were used for testing procedures. It would be helpful to add additional batteries or as stated use lithium batteries that can be charged more rapidly, last longer, and do not suffer as badly from memory effect.

4 Final Design and Results

4.1 Components and Assembly

Provided below is a list of components used and a detailed description of how those components are connected within the device. It is important to note however that the description below is for ideal circumstances and does not account for the fact that the device was unable to provide the voltage necessary for the boost converter to regulate.

4.1.1 Hardware Components

- Thermo-Electric Generators (TEGs)
- Boost Converter
- Battery Charger
- NiHM Battery Pack
- GPS Shield
- H-Bridge Driver
- Stepper Motor
- High Torque DC motor
- Mount

4.1.2 Charge and Discharge Circuit Configuration

All electrical components excluding the TEG, were contained in the base of the device and were mounted inside the base with Velcro. Mounting the components with Velcro instead of securing them with screws or another adhesive ensured that the components would not be jostled around and allowed for easy access to the components during testing and modifications. The following is comprehensive list of how the hardware components were connected and how they operated.

- The TEG is connected to the boost converter and it must provide with a minimum of 3[V] to operate properly.
- The boost convert is then connected to the battery charger and regulates the voltage provided to 12[V].
- The charge and discharge states of the battery charger is controlled by the red switch mounted on the base of the device.
- If the switch is in the charge configuration the battery charge will charge the NiHM battery pack at 0.5[A].
- If the switch is in the discharge state, power is provided to a 12[V] output port by the NiHM battery pack via the battery charger.

4.1.3 Solar Tracking

- The GPS Shield is mounted on the Arduino Mega and pings every thirty minutes so that it can provide the Arduino with an updated date, time and location.

- With the date, time and location provided the Arduino utilizes the SPA algorithm to calculate the Azimuth and Zenith angles and determines the rotation required about the vertical and horizontal axis.
- The Arduino then controls the stepper motor and the DC motor via the H-bridge driver, adjusting the dish to the correct orientation.

4.1.4 Base Design

- The base of the device was an Aluminum power box with a plexiglass top.
- Inside the base the hardware components mentioned in the previous sections were mounted on Velcro strips.
- The stepper motor controlling rotation of the dish about the vertical axis was mounted near the center of the base and geared with a 1-to-3 ratio to the vertical shaft.

4.1.5 Mounting System

- The shaft rests on a thrust bearing in the base to allow for smooth rotation.
- The aluminum yoke is mounted to the portion of the shaft extending through the plexiglass and is held in place with set-screws.
- The high torque DC motor is mounted on the base of the yoke and a belt runs from the motor to the rear of dish mount. This allows the DC motor to control the up-and-down motion of the dish.
- A convex mirror is mounted on an aluminum bar just below the focal point of the dish allowing light to be reflected back through the dish onto the TEG.

4.1.6 Cooling System

- For the cooling system, the radiator is mounted on aluminum brackets above the TEG oriented on the rear of the dish.
- Tubing runs from the radiator to the water-block upon which the TEG is mounted.

5 Project Summary

5.1 Challenges and Future Improvements

Overall the design came together quite well, however, were a team to take over the project in the future, there are a few possible redesigns that could be very beneficial.

5.1.1 Optics

Over the course of the project, the ability of our design to reflect heat back though the center of the dish was not adequately considered. During testing, it was found that the convex reflector mounted slightly below the focal point of the dish did not reflect heat as effectively as anticipated, despite the mirror itself getting exceptionally hot. Such a high loss in efficiency prevented the TEG from achieving the 3[V] required to activate the boost converter. It would be prudent to invest more time and research into why the heat was not reflected efficiently and devise an alternative solution. Because of this unforeseen issue, a last-minute redesign was implemented and the TEG was mounted at the focal point of the dish instead of the rear. The water cooling system was replaced by a CPU heatsink in a last minute attempt to get the required 3[V] output from the TEG.

5.1.2 Mechanical Design

The current design was handmade and as such, has imperfections that could be remedied with a machined design. It would be beneficial in the future to have a mechanical engineer model the design in a program such as Creo Parametric so that the mount and base could be made from machined aluminum.

5.1.3 Stepper-Motor Feedback

When implementing the DC-motor control, a potentiometer was connected to the shaft of the motor allowing the device to know the orientation of the dish about the horizontal axis at any given time. In the future, it would be beneficial for the stepper motor to have a similar feedback implemented so that it could automatically orient itself at startup.

5.1.4 Heat Dissipation and Cooling

For the TEG to produce a minimum of 3[V], it is necessary to provide adequate cooling to the cold side of the TEG. It would be safe to assume that the water cooling system tested and implemented in the design would have been adequate to accomplish this objective had heat been reflected through the dish effectively. It is recommended that the optics issue be addressed first and the water cooling system reimplemented in place of the CPU heatsink currently on the design.

5.2 Conclusion

The solar thermal generator project was successful in the overall implementation of the design, but fell short in a couple key areas. Perhaps the most important objective was to be able to effectively track the sun and the device does so quite well. To accomplish this objective, two motors were utilized to control the orientation of the dish and a software program was implemented that determined the Azimuth and Zenith angles precisely. The accuracy is somewhat affected by imperfections in the handmade mount and would benefit from a machined design. Despite these imperfections however, the device is still able to accurately track the sun in any location, under most conditions at any time of day.

The other key aspect of this project was power generation and in this regard the design fell short due to unforeseen issues with optical design. The TEG itself can produce up to 22[W] under ideal conditions, but because the TEG was not heated as expected, it was not even able to produce the 3[V] required to power on the boost converter. If thee optical issue can be remedied it is likely that the 3[V] can be exceeded and if an array of TEGs is connected in parallel and series, the objective of 20[W] output may be achieved.

The design turned out to be relatively inexpensive and ergonomic. In terms of portability the design could benefit from a smaller dish or a mechanism that allows the dish to be easily removed for transportation. However, the design is relatively lightweight and is very easy to use.

In conclusion, the project was multifaceted and unfortunately not all the specifications set at the beginning of the project were fulfilled and there were many lessons learned over the course of the year that would have been beneficial earlier on the planning phase of the project. However, many of the design objectives were achieved and such a complex and multifaceted design proved educational and challenging.

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7 Biography

Electrical: Ben Galivan
Responsible for chip cooling and heat dissipation methods and website design.

Software Engineer: Shazeen Tariq
Responsible for developing code required for the scope of the project. Specifies required equipment including microcontrollers and servos and ergonomics / user interface.

Software Engineer: Will Sidebottom
Responsible for developing code required for the scope of the project. Also, responsible for data management and geo tracking.

Electrical Engineer: Dylan Lee
Responsible for energy storage and battery productivity / power management and drawing specifications.

Electrical Engineer: Jason Galla
Responsible for power management and controls within the system as well as chip placement and functionality.

Project Manager/Electrical Engineer: Ernest Crabtree
Responsible for mechanical design and ensuring all project modules are completed and work together. Manages the budget and maintains a record of all credits and debits to project account. Any product or expenditure requests must be presented to the advisor, whom is then responsible for reviewing and the analysis of equivalent/alternate solutions. They then relay the information to the team and if the request is granted, order the selection. A record of these analyses and budget adjustments must be kept.

8 Appendix

8.1 Budget

No.	Description	Quantity	Cost/Unit $	Extended Cost $
1.	Experimental TEG's	5	$ 3.15	$ 15.75
2.	Ferro Fluid	4 Oz	$ 7.00	$ 28.00
3.	Heat Exchanger/Radiator	1	$ 16.99	$ 16.99
4.	Water Cooling Block	1	$ 14.98	$ 14.98
5.	Heat Sink	1	$ 18.00	$ 18.00
6.	Step-up Boost Converter	1	$ 5.40	$ 5.40
7.	Digital Thermometer	2	$ 4.99 + tax	$ 10.73
8.	Rare Earth Magnets	2	$ 2.98 + tax	$ 6.41
9.	Thermal Paste	2	$ 4.50	$ 9.00
10.	Parabolic collector/ Dish	1	$ 97.90	$ 97.90
11.	High Power TEG chip	1	$ 57.50	$ 57.50
12.	Microcontroller	1	$ 15.00	$ 15.00
13.	Dish Mount	1	$ 65.00	$ 65.00
14.	Servo Motor	2	$ 15.00	$ 30.00
15.	Custom Heat Sink	1	$ 25.00	$ 25.00

16.	Plastic Base/Box	1	$ 150.00	$ 150.00
17.	Battery Pack(NiMH)	1	$ 20.00	$ 20.00
18.	Electric components	1	$ 40.00	$ 40.00
19.	Hardware/ Miscellaneous	1	$ 30.00	$ 30.00
20.	Total Cost	1		$ 655.66