Solar Winds

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Abstract—**The motivation for this project is to reduce power draw on an electric grid during peak load times. The problem is storing power from an electric grid as thermal energy during non-peak load times. Our final result will be a mobile cooling system that uses stored thermal energy to deliver directional cooling, benchmarked by cooling a 2 cubic feet volume by 3.5ºF for 90 minutes. This project has and will be a compelling solution of storing electrical power as thermal energy to deliver cooling.**

I. INTRODUCTION

THE problem is storing power from an electric grid as thermal energy during non-peak load times. The problem is drastic. Cooling is a "peaky" load. Electric customers use cooling at similar times. For Holyoke Gas & Electric (HG&E), the cooling peak is around 3-4 PM [1]. This peak is most significant in late summer. According to ISO New England, the highest electric load occurs on a hot day in late summer [2]. Figure 1 shows the "duck curve," which exacerbates peakiness.

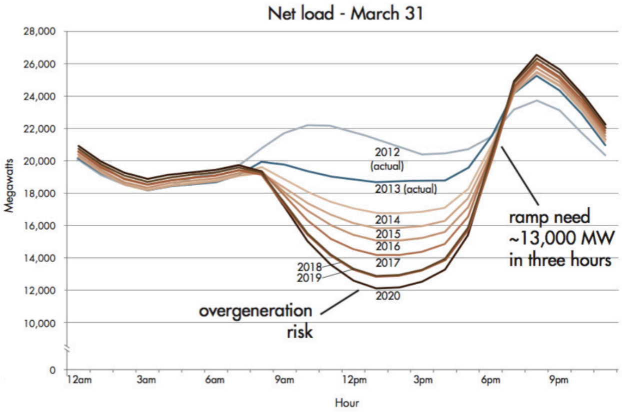

Figure 1. Duck Curve

The duck curve, first referenced by California ISO (CA ISO) for resembling a duck, demonstrates how a proliferation in distributed solar generation can make peaky load profiles peakier. During the day, solar panels generate power from sunlight, dropping the grid's midday net load. In the evening, the grid's load reaches peak. Dropping the midday load has led to significantly faster rise times, bringing on-call generators from zero to full speed within hours [3]. Customer-side solar installation makes this problem worse. The natural solution to the duck curve is energy storage: store available energy during non-peak times to use during peak times. Battery-based energy storage such as lithium batteries are limited in use, expensive at grid scale, potentially volatile, and degrade in the span of years [4]. In the energy sector, degradation is a major problem as thermal plants may last up to 50 years [5]. Properly-managed lithium batteries will last at most 10 years [6]. Although not in popular use, grid-scale research is underway in consortiums like NY-BEST [7]. Energy storage does not need to be purely electrical. Water's characteristics allows storage of thermal energy, a useful form of energy for cooling that we use to solve this problem.

Cooling solutions exist. Solutions include fans and air conditioning (A/C). Fans are a simple technology that use a motor to circulate air. Fans do not cool air. Any impression of cooling is because a breeze facilitates perspiration. The advantage of fans is low-cost. A/C units are more expensive. The Ice Bear is an existing solution that integrates with existing air conditioning systems [8]. During off-peak hours, the Ice Bear uses an A/C compressor to freeze ice in (what the manufacturer calls) an "ice battery." When cooling, the Ice Bear bypasses the A/C compressor, running air through the "ice battery" to provide cooling [8]. The disadvantages are immobility and high-cost. Our objective is to develop an impactful cooling solution.

The societal impacts of our solution are microscopic and macroscopic. Our "county fair" use case demonstrates the microscopic impact. Mobility is important to transport and deploy the unit in the county fair use case. However, our solution can be grid-scale. If thermal energy can be stored during non-peak load times, every household could individually store energy to reduce the peak's slope. Some developing countries schedule routine blackouts to all regions, guaranteeing daily individual power access. Our solution would excel in this context, replacing A/C units in developing countries or regions with unreliable power access.

Requirement	Specification	Value
portable	dry weight	< 150 lb
	size	< 20 cuft
cooling	air cooling	3.5º F
responsive	water cooling	< 6 hours

Table 1. List of system requirements and specifications

The county fair use case assumes a hot outdoor environment where power outlets are too far away for extension cords. The temperature is around 80ºF-85ºF, such that cooling is desirable. This use case assumes: the nearest outlet is more than 200 ft. away, users are located within 5 ft. of the cooling system, and users arrive at the event with a van or light-duty pickup truck (matching our form factor requirements as shown in Table 1). Our solution intends to noticeably cool a small directional volume. The county fair use case will be quite similar to our final demo. We will be outside in a tent on a relatively hot day, with the tent's temperature being reasonably comfortable.

We define the parameter of "noticeably cooler" as 3.5ºF [9], based on a paper quantifying the range of comfortable temperatures for sleeping subjects. According to Liu et al., their subjects had a range of comfortable temperatures that clustered within 1ºC [9]. From this, we assume a temperature difference of 2ºC is noticeable. This converts to approximately 3.5ºF. Our assumption bears out in practice, that people generally notice the difference between 68ºF and 71ºF. Our solution will transfer cooling from a thermoelectric cooler.

The thermoelectric cooler operates at 24 VDC and the fans at 12 VDC [10]. The thermoelectric cooler uses 192 W [10] while in use. The liquid cooler for the thermoelectric cooler uses 4 W [11]. When the out take fan is in use, it uses 36 W. The water pump uses 3.6 W [12]. When all components to the system are activated, the system uses a total of 240 W. The system cools one gallon of water by 10ºC, storing 157.3 kJ of thermal energy.

We imagine a form factor such that two average-strength people could carry the system out of a truck and deploy it. To this end, we have set a dry weight of 150 lb. With regards to power consumption, our system splits the difference between a fan and an A/C unit. We project we can cool a 2 cubic feet volume by 3.5ºF for 90 minutes (enough to cover the hottest time of day). This should be feasible with a moderate-size solar array. The commercial use case would be:

1. Arrive at the use location.
2. Unpack the cooling system from a work vehicle.
3. Deploy the solar array 20 to 50 ft. from the tent, under sunlight.
4. During the middle of the day, let the solar array store energy.
5. During late afternoon, activate the cooler as the temperature reaches its peak for the day.

II. DESIGN

A. Overview

Our system will store thermal energy in a liquid solution chilled by a thermoelectric cooler contained in a custom cooler box. The system technology is organized into five subsystems: cooling, control, feedback, tracking, and power. Figure 2 shows our block diagram and subsystems. Our subsystems rely on thermoelectric coolers, a microcontroller, a sensor array, and a power supply. Analysis of design alternatives led us to this technology. Due to optimizing cooling storage, we expect this technology to solve the problem.

Design alternatives are a compressor, ice maker and cold sink. Compressors are used in air conditioning units. Ice makers are commonly found in refrigerators. A cold sink, as shown in Figure 3, is a heat sink attached to the cold side of a thermoelectric cooler and submerged into the cooling tank. Ultimately, we did not proceed with these alternatives because they would not effectively solve the problem. A compressor has moving parts and undesirable thermodynamic effects [13]. An

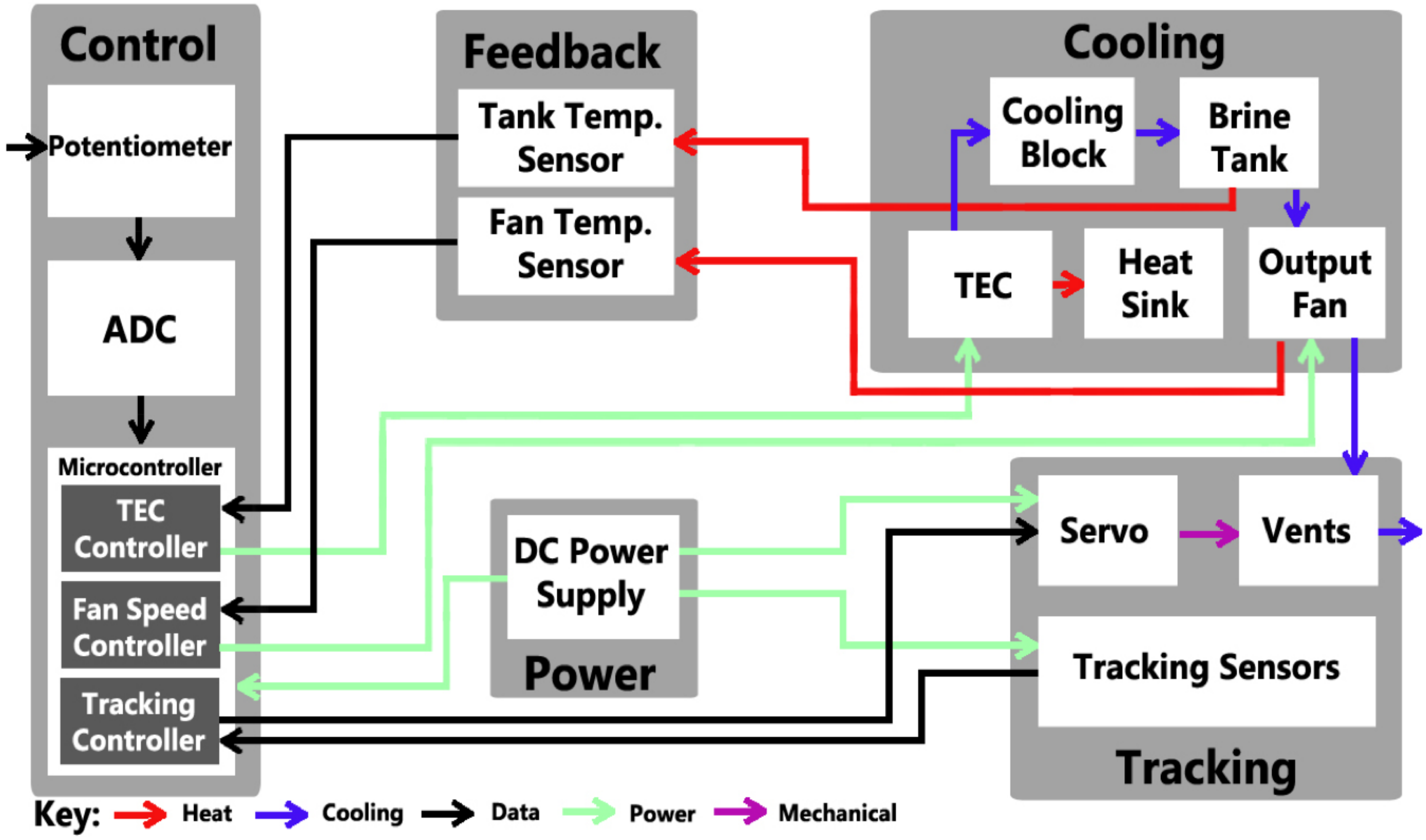

Figure 2. Solar Winds Block Diagram

ice maker has a power demand. Ice insulates energy within itself [14], inhibiting energy flow. A cold sink presents difficulties with heat transfer, cooling leaking and interfacing, and physical mounting.

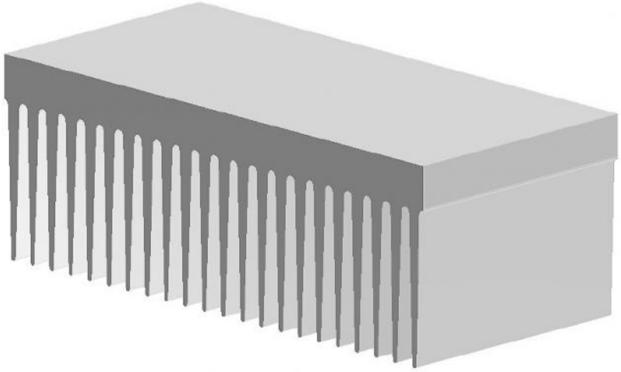

Figure 3. Cold Sink

Our solution cools by blowing air over a cooled liquid solution. Our current liquid solution is brine, or salt water. Brine is a low-cost, readily available, non-toxic substance. A characteristic of water is *specific heat*, meaning that a small change in the medium's temperature corresponds to a large amount of thermal energy stored [15]. Salt decreases water's specific heat, quickly adjusting to both temperature increases and decreases. Salt water decreases the freezing point, removing the concern of solidification. We intend to use a salinity of 10%, offering an improved specific heat over plain water. Maximum salinity is approximately 26% [16]. A concern of salt water can be corrosion. However, research shows corrosion from salt water is only problematic after an extremely long duration [17].

Our initial plan was to freeze ice, akin to the Ice Bear system mentioned above. However, ice is known for a low thermal conductivity [13]. A pond in the winter does not entirely freeze through: a layer of ice atop the pond insulates the water below. Freezing blocks of ice would not be feasible. Each frozen block would reduce the thermal conductivity [13], increasing the difficulty of freezing the next block. Brine freezes at a lower temperature, storing thermal energy without complications due to ice in the energy storage process. To reach our proposed air temperature delta, we do not expect the liquid solution's temperature to drop below 0ºC, concluding we could use alternatives to brine.

We cooled the liquid solution with a "cold sink," a heat sink applied to the cold side of a thermoelectric cooler. We assumed that if we submerged the cold sink in brine, the cold sink would get cold and draw heat out of the liquid solution, cooling the liquid. However, this raised two issues. First, we did not know where to install the cold sink. If we wanted the cold sink to be in the side or bottom of our tank, we would have to drill a hole in our tank and figure out a way to prevent the tank from leaking afterward. More pressing, we found during testing that our cold sink did not get cold. Our thermoelectric cooler is 50mm square [10]. We tested our cold sink hypothesis using two heat sinks on both sides of the thermoelectric cooler. However, the two heat sinks had a much larger footprint than our thermoelectric cooler. This meant there was a significant amount of surface area where the two heat sinks were only separated by approximately 2 mm of air. There was little to stop the heat sinks from transferring heat from the heat sink we wanted to be hot to the heat sink we wanted to be cold. We realized that we needed to further isolate the heat coming from the thermoelectric cooler from the cooling effect we want. Our current prototype, as shown in Figure 4, uses a pump that circulates liquid from the tank, across the thermoelectric cooler, around the tank in a hose, then back in the tank proper. This way, we can cool liquid away from the cooler to ensure that the heat dissipated by the thermoelectric cooler does not affect the liquid in the tank.

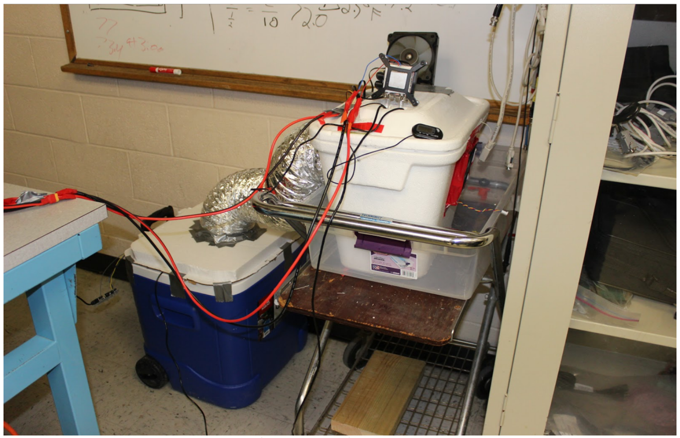

Figure 4. Solar Winds MK-II Prototype

The tank can be cooled using a compressor-based heat exchanger [14]. However, we realized that if we used a heat exchanger, we would have to manage coolants and compressors and pipe organization. This would present implementation difficulties that are non-essential and distract from solving the problem. By comparison, thermoelectric coolers are solid-state [10], leading to a more effective solution. Ease of transport is another key specification of our system, and a solid-state cooler means there are fewer moving parts, easing transportation.

Much of our current progress has been defined by rethinking pieces of our prototype after facing design flaws. Our initial plan of using ice was scrapped after realizing that a liquid solution is most optimal. Our original plan of using a "cold sink" was changed after bench tests showed that our cold sink would not get cold. Our initial idea of building a prototype around a foam cooler was changed because that foam cooler sprung a significant leak after simply filling it with water. Going forward will require both refining our prototype and integrating additional subsystems. On the refining side, this involves designing a PCB microcontroller and refining the feedback loops the microcontroller would run on. On the integrating side, we need to add user input and integrate a data collection tool. Our design for each subsystem is below.

B. Cooling Subsystem

The cooling subsystem circulates a liquid solution through a pumping system and cools the solution using a thermoelectric cooler. Our cooling subsystem is built from a Laird HiTemp ET series thermoelectric cooler [10], a DIYhz aluminum radiator cooling block [18], a Corsair Hydro liquid cooler heat sink [11], and a custom cooler to contain the liquid solution. A CAD model of the custom cooler is shown in Figure 5.

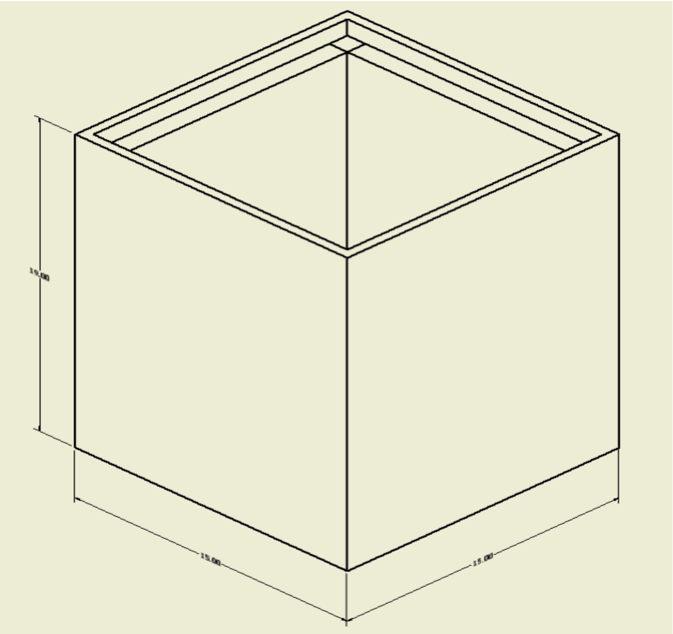

Figure 5. CAD Model of Custom Cooler

For spring 2019, the ECE student machine shop is closed, without a set date to reopen. Our team has been advised by Shira Epstein, Director of Campus Makerspaces, to change our cooler design to a plastic tub container. The machine shop's closure and the advisement against our proposed design is under review by our team. One concern is mechanical waves generated from motion. For our mobile system, these waves would carry through the non-rigid plastic tub walls. We are rapidly determining the appropriate solution.

When demonstrating MDR deliverables as shown in Table 2, this subsystem successfully stored electrical power as thermal energy. This has been demonstrated by cooling an environmentally insulated 2 cubic feet volume by 3.5º F for 1.5 hours. We tested and analyzed the results by verifying a temperature drop. There is a difference between our use case of directional cooling in an open environment and benchmarking of our cooling specification in a closed environment. To quantify our solution, our benchmark uses an environmentally insulated polystyrene cooler with a thermal resistance between the box and environment, or "R-value," of R-5 [19].

C. Control Subsystem

The control subsystem allows user control of our energy storing cooling solution. Our plan for the control subsystem includes a microcontroller, control circuitry, and feedback control software. For midway design review, our team used an Arduino microcontroller to demonstrate our deliverables. We plan for our control subsystem to be a custom printed circuit board (PCB). We plan to use EagleCAD to design the PCB. This PCB would house an ATmega 32 [20] or similar microcontroller. The microcontroller will implement feedback control for cooling both the liquid solution and output air. The control subsystem may be a binary "bang-bang" controller [21]. The user will control the desired level of output cooling with a potentiometer, akin to the cooling knobs in older car air conditioners. We will also implement voltage controllers for the thermoelectric cooler and cooling fans. The control software will be refined after the comprehensive design review for the final project review. To test this subsystem, we will define a water and air temperature test threshold. To analyze the test results, we will verify if the fan speed and thermoelectric cooler temperature adjust when the test threshold is reached.

D. Feedback Subsystem

The feedback subsystem will report data from the cooling subsystem to the control subsystem. We plan for the feedback subsystem to use sensors to measure the temperature of the chilled air and liquid solution. The DS12B20 integrated circuit sensor [22] has been selected to measure tank temperature because it is waterproof. The LM35 integrated circuit sensor [23] has been selected to measure output air temperature because it is readily available. When demonstrating MDR deliverables, this subsystem measured temperatures in the brine tank and in the volume of air being cooled. To test this subsystem, we will use the microcontroller to collect readings of different temperatures. To analyze the test results, we will verify these readings match with a calibrated thermocouple.

E. Tracking Subsystem

The tracking subsystem will track users. Our plan to implement the tracking subsystem is develop an array of sensors. Parts for the tracking subsystem include a servomotor, an interrupt and sensors. The servomotor will direct vents towards users. The interrupt will allow users to manually interrupt the tracking subsystem. The sensors will detect user motion. The tracking subsystem will target cooling towards users. To test this subsystem, we will set up a controlled trial for the sensors to move the servomotor. To analyze the results, we will verify or falsify the test results against the expected results of the controlled trial.

F. Power Subsystem

The power subsystem will provide power to each subsystem within our solution. This subsystem plans to mirror electrical specifications of photovoltaic panels and charge controllers, so that integration with solar systems is relatively simple. The power subsystem will run at 24 volts and provide around 300 watts of power for each thermoelectric cooler used in the cooling subsystem. The power subsystem will be source-agnostic, since the functionality of our system is storing electrical power as thermal energy. Integrating solar power for our final project review would be an ambitious and expensive reach goal [24], [25], [26]. To achieve that, we would need to purchase a solar panel [24], charge controller [25], and a specialized light [26]. The specialized light would replicate sunlight [26], a rare commodity due to the lab being in New England and having no windows. We can implement solar in our power subsystem if and only if we are given the budget to do so. To test this subsystem, we will use a multimeter to measure voltage and current. To analyze test results, we will verify the other subsystems are operating under the supplied power conditions.

III. PROJECT MANAGEMENT

TABLE II

MDR DELIVERABLES

MDR Goal	Status
Cool 2 cubic feet area by 3.5° F for 1.5 hours	Accomplished
Fit a form factor such that two people can carry it into a van or light-duty pickup truck	Accomplished
Provide a paper design on sensors to enable directionality and prediction	Accomplished

Table 2. MDR Deliverables

Our team has grown from the beginning of our project until present, continually learning and growing together. As a baseline, we hold weekly team meetings, advisor meetings, and building sessions. Within the team, we delegate challenging but manageable tasks that offer team members the opportunity to grow for themselves, thus growing our collective knowledge and expertise. Each iterative design review further solidifies our team's bond and commitment to solving the problem.

In progressing to our midway design review, our team made significant accomplishments by demonstrating critical functionality through implementing our cooling subsystem. The objective of our cooling subsystem is to circulate a liquid solution through a pumping system and cool the solution using a thermoelectric cooler. Our current accomplishment is implementing the cooling subsystem. In detail, our cooling subsystem uses a Laird HiTemp ET series thermoelectric cooler [10], a DIYhz aluminum radiator cooling block [18], and a Corsair Hydro liquid cooler heat sink [11]. These parts effectively store electric power as thermal energy, with the electricity being inputted into the thermoelectric cooler and the thermal energy being stored in the liquid solution.

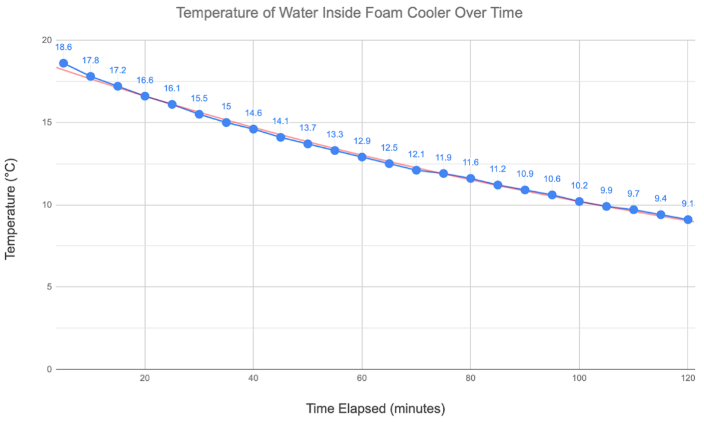

Figure 6. Graph of Water Temperature over Time

Although our team has progressed past the midway design review, there is additional functionality to be incorporated. The additional functionality will be delivered upon building the additional subsystems: control, feedback, power, and tracking. These subsystems were thoroughly detailed above in Section 2, Design. Generally, the objective of these subsystems are as follows. The control subsystem enables user control of the cooling subsystem. The feedback subsystem reports data from the cooling subsystem to the control subsystem. The power subsystem delivers power to each subsystem. The tracking subsystem tracks users with an array of sensors.

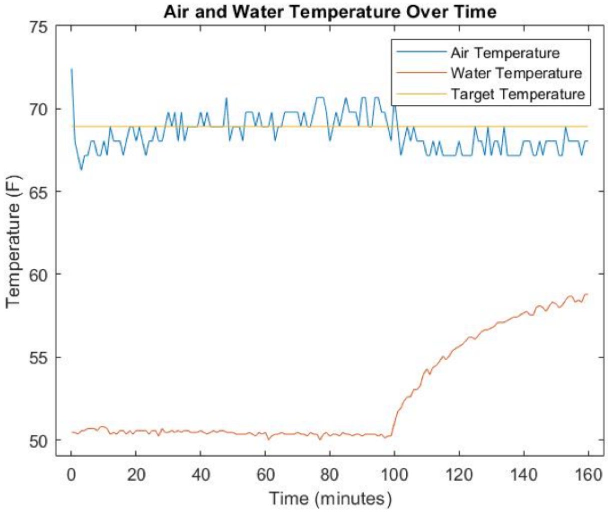

Figure 7. Graph of Air and Water Temperature over Time

Each team member contributes individual expertise derived from their experiences and relevant coursework. Most of the relevant coursework has been taken in Fall 2018. Jayme enrolled in ECE 373, Software Intensive Engineering. Ajey, Jayme, and Richard enrolled in ECE 597ED, Electricity Infrastructure and Delivery in the Developing World. Jason enrolled in ECE 558, Introduction to VLSI Design, building his background in circuit and layout design. Jason and Nicholas enrolled in ECE 563, Introduction to Communication and Signal Processing. Ajey, Nicholas and Richard enrolled in ECE 580, Feedback Control Systems. This will help in designing our control and feedback subsystems. For spring 2019, Ajey and Richard enrolled in MIE 570, Solar & Direct Energy Conversion, helping them characterize and model the system to run off photovoltaic panels. These courses provide the educational background to motivate and inform our project's design and build.

From team members experiences, our team has expertise ranging from 3D modeling to photovoltaics. Jayme and Richard have experience in 3D modeling and design. Richard has experience in photovoltaic panels. Jayme has experience in high level programming, which will be useful for data collection. Jayme has previous leadership experience, leading him to take a project management role. Ajey is quite comfortable with writing, leading him to take a communications role. Ajey and Nicholas have built experience in thermodynamics over Fall 2018. Richard has reviewed literature for heat transfer analysis. Ajey and Nicholas have experience in MATLAB programming. Nicholas has developed expertise in characterizing the performance and power requirements of cooling. Jason has experience in circuit layout design and testing. Our team is made up of well-rounded and experienced students.

Outside of weekly meetings, the team meets several times a week and maintains real-time communication. The team works

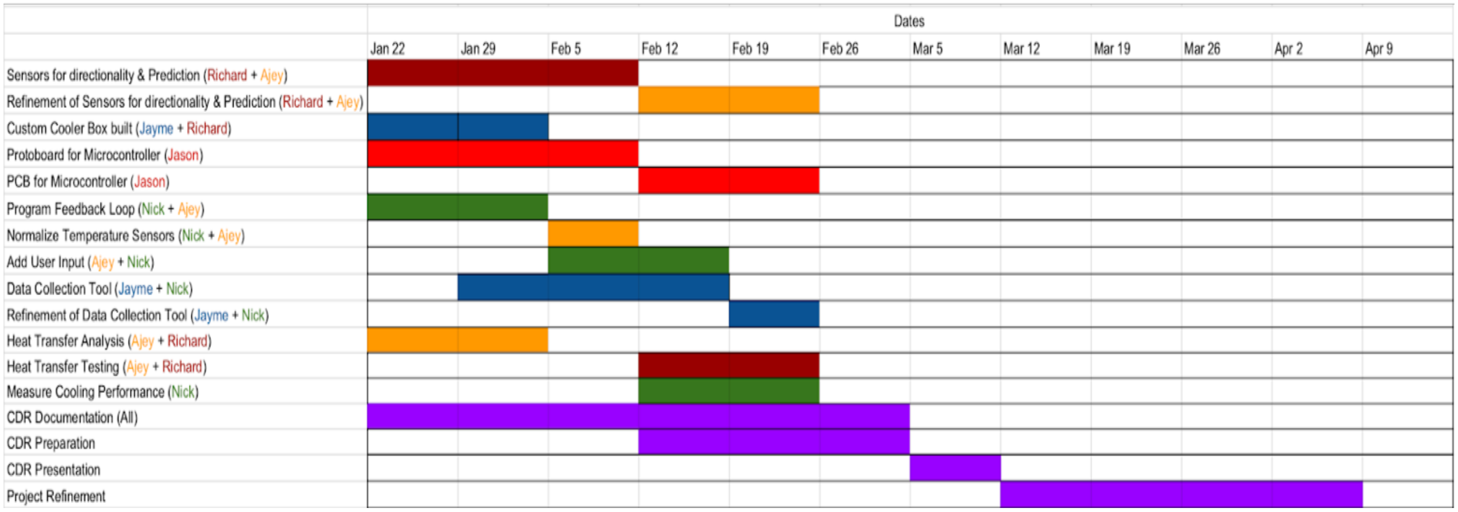

Figure 8. Gantt Chart

by holding regular building sessions where team members discuss challenges with their assigned tasks, receiving peer input and guidance. Team building sessions provide a motivated environment to finish delegated tasks. These sessions have been productive and when we found our prototype testing results, as seen in Figures 6 and 7. Figure 6 shows a decrease in water temperature over time. Figure 7 shows air temperature drop below our target temperature, verifying our hypothesis. Our project tasks have been assigned and tracked using a Gantt chart, as shown in Figure 8. Tasks were delegated and balanced based on individual expertise and interest level.

IV. CONCLUSION

The current state of the Solar Winds project is a cooling system that demonstrates the critical functionality of storing electrical power as thermal energy. We arrived at the midway point by working together as a strong team. During the building process, the team had frequent meetings and building sessions. Moving forward, we plan to complete our system by implementing control, feedback, power, and tracking subsystems. These additional subsystems will demonstrate the major functionality of our finished energy storage cooling system. Our team has and will continue to expect difficulties in design and implementation. To overcome such difficulties, we investigate design alternatives, objectively examining whether these alternatives contribute towards or detract from reaching an effective energy storage cooling solution.

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