Solar Winds

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***Abstract*—The motivation for this project is to reduce power draw (particularly due to cooling) 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 is a mobile cooling system that uses stored thermal energy to deliver directional cooling. Our product will have macroscopic impact as scheduled blackouts occur in developing countries. This project is 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. Grid administrators (such as ISO New England) work to ensure constant-access to electric power. The problem is drastic as 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.

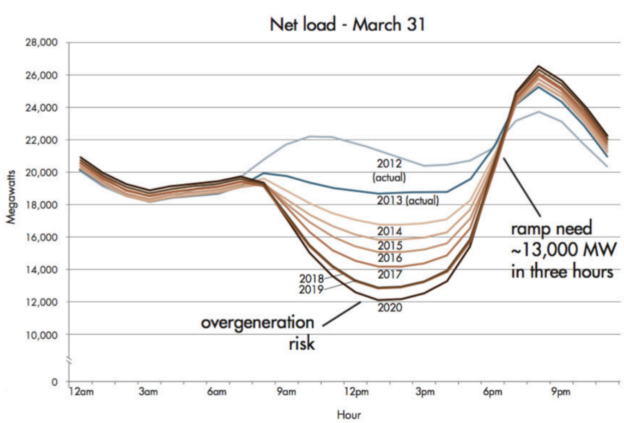

Figure 1. Duck Curve.

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]. On-call generators have worse environmental impact compared to power generators with slow ramp-up times. (Generation sources include using coal, nuclear, natural gas, hydroelectric, solar, and wind.) Customer-side solar installation has made the sharp demand slope worse by further removing daytime grid demand. 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.

Power quality is vital to a society. Generated power must be instantly delivered and consumed. An imbalance of power generation to demand on an electric grid affects the grid's voltage and frequency. Grid voltage has a 5 % tolerance, with 120 V ranging from 114 V to 126 V. Our solution will excel in electric grids with constant-access fixed-pricing, constant-access tiered-pricing (based on peak times) or scheduled (rolling) blackouts. In all three mentioned grid settings, power can be stored during non-peak times for peak times. Respectively, examples are United States [8], Belarus [9], and Iraq [10].

Energy is stored power. Types of energy include mechanical, gravitational, electrical, magnetic, radiant, chemical, nuclear, and thermal. Our solution stores thermal energy. Thermal energy is defined as "the combined microscopic kinetic and potential energy of the atoms - the energy of the jiggling atoms and stretching bonds" [11]. Thermal energy is dependent on system temperature. Heat is defined as "the energy transferred between a system and the environment as a consequence of a temperature difference between them" [11]. Heat energy can be transferred via conduction, convection, radiation, and evaporation. In science, conventions or established practices are adopted such as electrical conventional current being opposite electron flow. It is convention that a higher temperature value corresponds to a higher thermal energy. Our solution opposes this convention by storing cool thermal energy.

Our project has macroscopic and microscopic societal impact. Macroscopic impact would be grid-wide deployment of Solar Winds thermal batteries in every home. Power generation from clean technologies with slow startup times (such as nuclear and hydroelectric shown in Figure 2 below) could be increased due to increased storage capacity across an electric grid. This would increase the minimum generation during midday and decrease the sharp slope in the duck curve above.

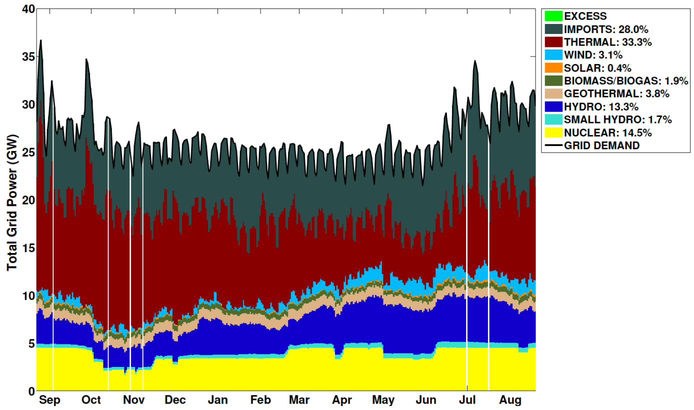

Figure 2. Grid Power Demand in California 2011-2012.

In remote setting without grid access, our solution has microscopic impact. Microscopic impact is demonstrated by storing cooling for later use. In Iraq where they have scheduled blackouts, A/C units are not reliable as they require constant power supplied. Our solution would provide each household with a solution similar to A/C, only requiring minimal operating power for a fan from solar. In oceanside communities, our solution is renewable as our battery can be fueled by salt water and preserve limited fresh water supplies for drinking. Our "county fair" use case also demonstrates microscopic impact.

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).

We define the parameter of "noticeably cooler" as 3.5ºF [12], 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 [12]. 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.

Existing cooling solutions include fans, air conditioning (A/C) and the Ice Bear. Fans use an electric motor to circulate air. Fans do not cool air. Any impression of cooling is because a breeze facilitates perspiration. Fans are inexpensive. A/C units are more expensive than fans. The Ice Bear solution integrates with existing A/C technology. During non-peak times, 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 compressor and runs air through the "ice battery" to provide cooling [13]. Disadvantages of the Ice Bear are immobility and high-cost. Our objective is a mobile cooling system. One possible commercial production of our energy storage solution would be a transportable thermal battery to provide cooling when discharged at outdoor events, like a county fair.

Our solution transfers cooling from thermoelectric coolers (TEC). The thermoelectric coolers operate at 24 VDC and the fans at 12 VDC [14]. Each thermoelectric cooler uses 190 W [14] while in use. Each TEC has a corresponding liquid cooler using 2 W [15]. The water pumps each use 5 W [16]. When all components to the system are activated, the system uses a total of 520 W. The system cools five gallons of water by 10ºC, storing 790 kJ of thermal energy.

TABLE I

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

Table 1. List of system requirements and specifications.

II. DESIGN

A. Overview

Our system stores thermal energy in a liquid solution chilled by thermoelectric coolers contained in a custom cooler box. The system technology is organized into six subsystems: cooling, control, sensors, tracking, power, and computing. Figure 3 shows our block diagram and subsystems. Our subsystems rely on thermoelectric coolers, a custom printed circuit board (PCB) with an ATmega328P microcontroller [17] and an ultrasonic sensor array [18], liquid coolers [15], feedback-controlled relays [19], and a Raspberry Pi single-board computer [20]. We chose this suite of technology after analyzing design alternatives.

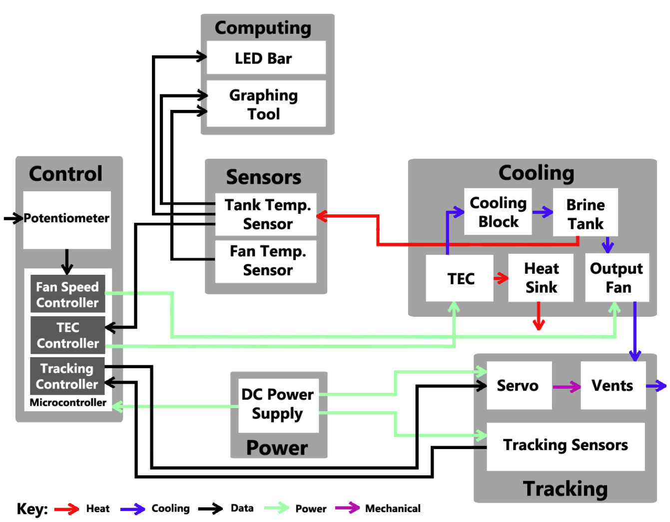

Figure 3. System Block Diagram.

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 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 [21]. An ice maker has a power demand. Ice insulates energy within itself [22], inhibiting energy flow. A cold sink presents difficulties with heat transfer, cooling leaking and interfacing, and physical mounting.

Our solution cools by blowing air over a cooled liquid solution. Our final liquid solution is plain water. We experimented with brine, or salt water. Brine is a low-cost, readily available, non-toxic substance available to shoreline communities that may want to preserve fresh drinking water. We found salt corrosion has minimal impact on our system, as the water exclusively interacts with the pumps, hose lines, and custom cooler inner shell. The custom cooler shell is made from a plastic non-corrosive material. Research shows corrosion from salt water is only problematic after an extremely long duration [21] and preservation of drinking water may be more important than tens of dollars in pumps after many years.

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 [19]. 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. Users can use a salinity of 10% and achieve an improved specific heat over plain water. Maximum salinity is approximately 26% [20].

Our initial plan was to freeze ice, akin to the Ice Bear system mentioned above. However, ice is known for a low thermal conductivity [24]. A pond in the winter does not entirely freeze through as 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 [24], increasing the difficulty of freezing the next block. Brine freezes at a lower temperature, storing thermal energy without

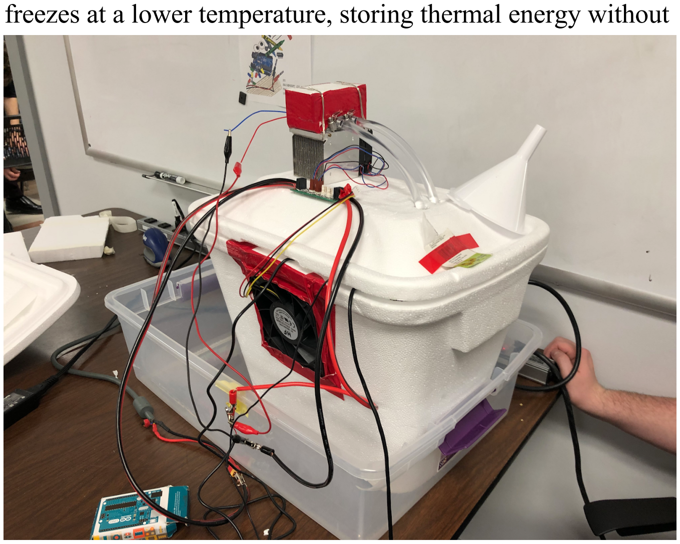

Figure 4. MDR System Build.

complications due to ice in the energy storage process. To reach our proposed air temperature delta, the liquid solution's temperature did not 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 [14]. 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 midway solution is contrasted to our final solution in Figures 4 and 5. Our final solution, as shown in Figure 5, uses pumps that circulates liquid from the tank, across the thermoelectric coolers, around the tank in hoses, then back in

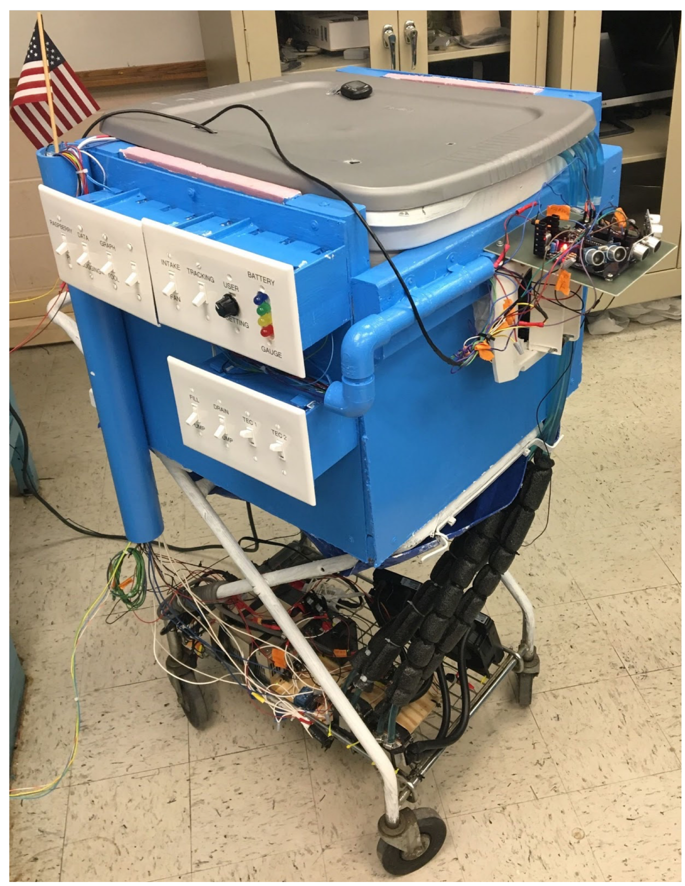

Figure 5. FPR System Build.

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.

The tank can be cooled using a compressor-based heat exchanger [22]. 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 [14], 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.

Our yearlong 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. This yearlong project required both refining our prototype and integrating additional subsystems. Our final design for each subsystem is detailed below.

B. Cooling Subsystem

The cooling subsystem circulates a liquid solution through a pumping system and cools the solution using thermoelectric coolers. Our cooling subsystem is built from two Laird HiTemp ET series thermoelectric coolers [14], two DIYhz aluminum radiator cooling blocks [22], and two Corsair Hydro liquid cooler heat sinks [15], and a custom cooler to contain the liquid solution. Our custom cooler was primarily built in the student machine shop using parts readily available at home improvement stores (such as Home Depot and Lowes). The build was made of wood for the frame and outer shell, R-5 foam board insulation [23], and PVC piping for cable management. When demonstrating FPR deliverables (as shown to the right in Figure 7), this subsystem successfully stored electrical power as thermal energy.

At the midway design review, we used a closed environment to benchmark and demonstrate critical functionality. We demonstrated by cooling an environmentally insulated 2 cubic feet volume by 3.5ºF 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 that we had at FPR and demo day, and benchmarking of our cooling specification in a closed environment. To quantify our solution, our benchmark used an environmentally insulated polystyrene cooler with a thermal resistance between the box and environment, or "R-value," of R-5 [23].

C. Control Subsystem

The control subsystem allows user control of our energy storing cooling solution. This subsystem includes a microcontroller, control circuitry, and feedback control software. For midway design review, our team used an Arduino microcontroller to demonstrate our deliverables. For final project review, we used a custom printed circuit board (PCB) designed in Altium Designer. Our PCB houses an ATmega328P microcontroller and sensor array. The microcontroller implemented feedback control for cooling the liquid solution.

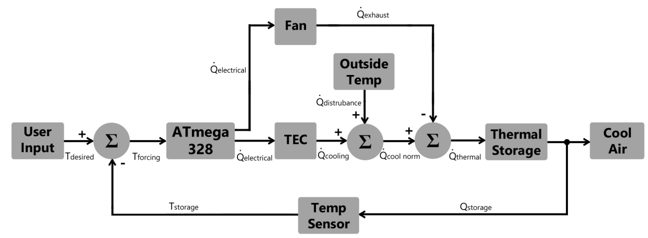

Figure 6. Feedback Control Diagram.

As shown above in Figure 6, the user controlled the desired cooling with a potentiometer, akin to the cooling knobs in older car air conditioners. We implemented controllers for the thermoelectric cooler and cooling fans. The control software has been refined after the comprehensive design review for the final project review. To test this subsystem, we ran our data collection tool and adjusted the temperature from low (15ºC) to medium setting (12.5ºC), as shown in Figure 7. Figure 7 verifies feedback control.

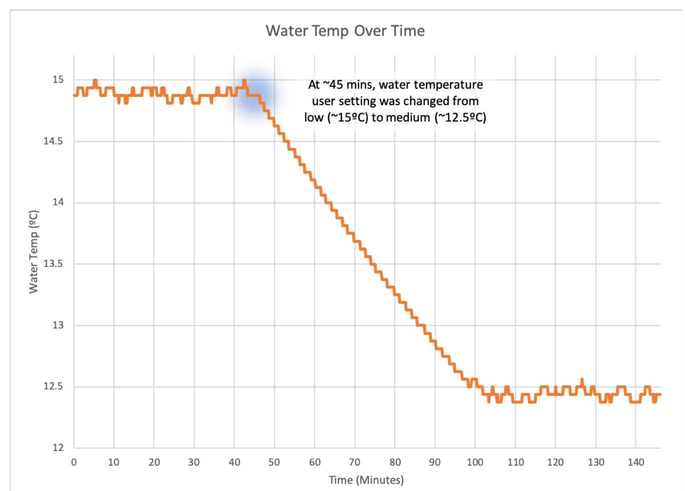

Figure 7. Verification of Feedback Control.

D. Sensors Subsystem

The sensors subsystem reports data from core system temperature sensors to the control and computing subsystems. Our sensors subsystem measured temperature of the chilled air and liquid solution [25]. We selected the waterproof DS12B20 integrated circuit sensor [26] to measure air and water tank temperature. We selected the LM35 integrated circuit sensor [27] to measure output air temperature because it is readily available. To test this subsystem, we used both the microcontroller and single-board computer to collect temperature readings. To analyze the test results, we successfully verified these readings by comparing to a calibrated thermocouple.

E. *Tracking Subsystem*

The tracking subsystem tracks users to deliver directional cooling. Our implementation is a sensor array mounted at the front of our system. Parts include a servomotor [28], ducting with vent fins [29], an interrupt and ultrasonic sensors [18]. The servomotor directs vents towards users, efficiently delivering cooling. In a closed room environment, temperature will not instantaneously reach thermal equilibrium. Therefore, directionality provides efficiency by initially cooling the targeted user. In an open environment, directionality provides cooling similar to air conditioning in a convertible on a hot summer day. An interrupt allows users to manually interrupt tracking. Sensors detect user motion. To target users, a running median function on the ultrasonic sonar sensors input is run to determine an accurate distance. The servomotor points towards the sensor (in the array) with the lowest measured distance. To test this subsystem, we set up controlled trials for the sensors to move the servomotor. We successfully verified test results against expected results from the controlled trial.

F. *Power Subsystem*

The power subsystem provides power to each subsystem within our solution. This subsystem mirrors electrical specifications of photovoltaic panels and charge controllers, so that integration with solar systems is relatively simple. The power subsystem runs at 24 volts and provides around 190 W for each TEC. The power subsystem is source-agnostic, since the functionality of our system is storing electrical power as thermal energy. Integrating solar power for our final project review was an ambitious and expensive reach goal [32], [33], [34]. To achieve that, we would have needed to purchase a solar panel [32], charge controller [33], and a specialized light [34]. The specialized light would replicate sunlight [34], a rare commodity due to the lab being in New England and having no windows. Due to the already expensive and ambitious nature of this project (with total expenses of $1290), we could not afford solar integration. To power some components such as liquid coolers and fans, we salvaged a free Xbox 360 12VDC Power Supply, as we had run out of funds. To analyze the power subsystem, we completed a full report on System Power Flow and Efficiency, as detailed below in Section 3.

G. *Computing Subsystem*

The computing subsystem uses a Raspberry Pi 3 Model B+ single-board computer to process system inputs and output data logs, graphs and control signals for a LED battery gauge. After consulting with Professor David Irwin, we determined there was no standard data format adopted in the Green Computing Industry. Therefore, we moved forward with outputting system data logs as CSV (comma separated value) files. Figure 8 shows our directory of timestamped data logs. Figure 9 shows the raw text of a CSV file. These logs were inputted to another Python script that produced graphs of sensor data versus time, as shown to the right in Figure 10. The target temperature ranges for battery storage levels were from ambient temperature to 17ºC, 17ºC to 14ºC, 14ºC to 12ºC, and below 12ºC. These temperature ranges were determined after extensive analysis of system characteristics by Ajey. The computing subsystem was limited to this functionality partly due to cybersecurity concerns. Without time to develop security practices, Jason and Richard decided not to allow core system functionality access over the Internet. The data logs were particularly helpful in testing feedback, as we plotted feedback functionality (as shown above in Figure 7) after letting the system automatically sample the sensors.

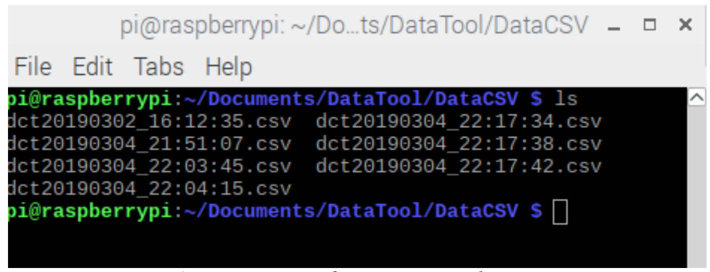
```
pi@raspberrypi: ~/Do…ts/DataTool/DataCSV
File Edit Tabs Help
pi@raspberrypi:~/Documents/DataTool/DataCSV $ ls
dct20190302_16:12:35.csv  dct20190304_22:17:34.csv
dct20190304_21:51:07.csv  dct20190304_22:17:38.csv
dct20190304_22:03:45.csv  dct20190304_22:17:42.csv
dct20190304_22:04:15.csv
pi@raspberrypi:~/Documents/DataTool/DataCSV $
```

Figure 8. Directory of Timestamped Data Logs.

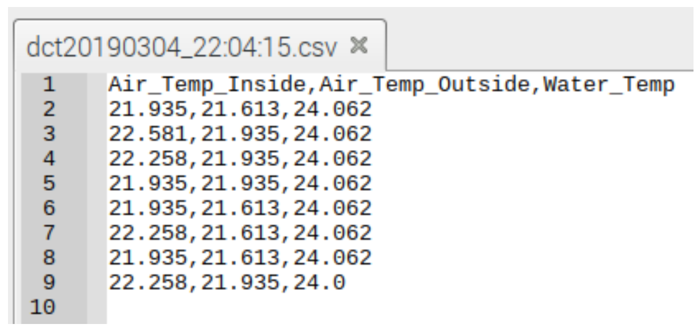
```
dct20190304_22:04:15.csv
1  Air_Temp_Inside,Air_Temp_Outside,Water_Temp
2  21.935,21.613,24.062
3  22.581,21.935,24.062
4  22.258,21.935,24.062
5  21.935,21.935,24.062
6  21.935,21.613,24.062
7  22.258,21.613,24.062
8  21.935,21.613,24.062
9  22.258,21.935,24.0
10
```

Figure 9. Raw Text of CSV File.

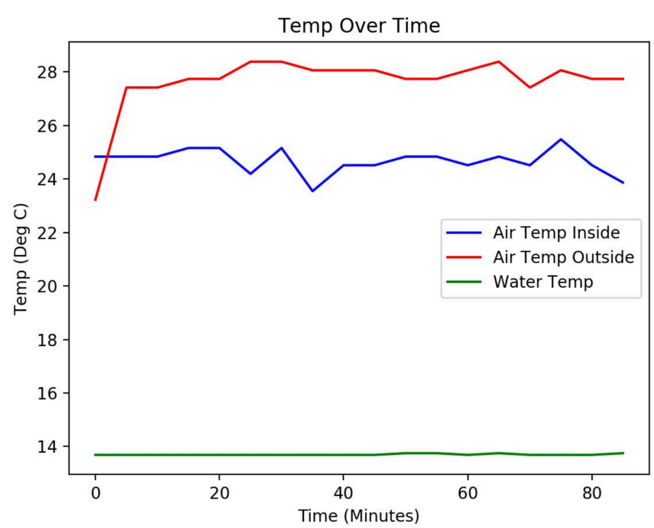

Figure 10. Graphical Data Presentation Tool.

III. System Power Flow and Efficiency

An efficiency report was a deliverable for the final project review, written with the goal of tabulating power flows and energy storage within our system. Given that our project falls within the realm of renewable energy and "green technology," efficiency is a relevant metric to consider in our system, even if not an important specification itself. In this power flow analysis efficiency report, we account for all energy inputs and outputs, including thermal losses and energy storage. We then derive efficiency figures from these measured power flow values.

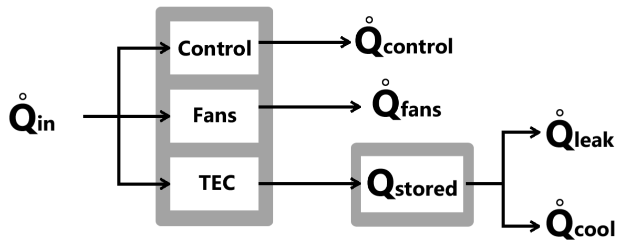

Figure 11. Efficiency Flow Diagram.

A. Methodology

Our procedure was to measure voltage and current throughout our system. To measure voltage, we applied the two probes of the multimeter across each element (as expected). To measure current, we closed the switches on our user interface. By creating an open circuit, we were able to effectively measure current through each element.

For thermal energy storage, we measured temperature to determine thermal energy. Given the mass and specific heat of water, we could determine energy storage as directly proportional to the temperature differential between the water and ambient air, as shown below in Equation (8).

For output cooling, we were able to rate the cooling ability by tracking the change in temperature of the water over time. By calculating the change in energy storage divided by a given time period, we could determine a rating for the cooling capacity of the Solar Winds system.

B. Results

In our analysis, we obtained experimental results. Electrical power is measured in Watts. Thermal energy is measured in BTU, which is the standard unit for HVAC (Heating, Ventilation, and Air Conditioning) applications. Output cooling is measured in BTU per hour, which is also standard for HVAC applications. Below are the experimental results we obtained in our analysis.

We measured energy stored and lost in the thermal storage system with Equation (1) of specific heat. Q stands for energy in joules, Q_C for heat removed, Q_H for heat added, m for mass in kilograms, c for specific heat in joules per kilogram times Kelvin, ΔT for change in temperature in Kelvin or degrees Celsius, T_C for cold temperature, T_H for hot temperature, ρ for density in kilograms per meter cubed, and V for volume in meter cubed.

$$Q\ (J) = m\ (kg) * c\ \left(\frac{J}{kg*K}\right) * \Delta T \quad (1)$$

$$\rho = 1000\ \frac{kg}{m^3} \qquad \textit{for liquid water} \quad (2)$$

$$V = 5\ gallons * \frac{1\ m^3}{264.172\ gallon} = 0.0189271\ m^3 \quad (3)$$

$$m = \rho * V \quad (4)$$

$$\boldsymbol{m} = 1000\ \frac{kg}{m^3} * 0.0189271\ m^3 = \mathbf{18.927\ kg} \quad (5)$$

$$c = 4.19 * 10^3\ \frac{J}{kg*K} \qquad \textit{for liquid water} \quad (6)$$

$$Q\ (J) = 18.927\ kg * 4.19 * 10^3\ \frac{J}{kg*K} * \Delta T \quad (7)$$

$$Q\ (J) = 79304.13 \frac{J}{K} * \Delta T \quad (8)$$

The mass of 5 US liquid gallons is 18.927 kilograms, as calculated in Equation (5). The mass was found when multiplying the known water density by the volume (after converting US liquid gallons into SI units of meters cubed). As the mass and specific heat are constants, we were able to calculate energy storage by measuring temperature differentials.
Power and energy measurements are shown below in Table 2.

TABLE II

Metric	Unit	Value
Power delivered from 24VDC Power Supply	W	380
Power delivered from 12VDC Power Supply	W	130
Power consumed by PCB	W	0.5
Power consumed by servomotor	W	12 (peak)
Power consumed by (two) TECs	W	370
Power consumed by (two) liquid coolers	W	80
Power consumed by (two) water pumps	W	10
Power consumed by intake fan	W	50
Stored thermal energy	BTU	750
Energy storage rate	W	13.45
Energy loss through heat leakage	BTU/hr	8

Table 2. Table of Power and Energy Measurements.

When excluding the intake fan and servomotor from power draw, our Solar Winds system draws 470W. 13.5 Watts is stored. In testing, the system discharges energy at double the rate as it stores energy. Using Equation (9) below, we found a coefficient of performance (COP) of 0.056. The rating used by air conditioners is Energy Efficiency Ratio (EER). Equation (10) below shows how to convert from COP to EER.

$$COP_{cooling}\left(\frac{W}{W}\right) = \frac{Q_C}{Q_H - Q_C} = \frac{T_C}{T_H - T_C} \quad (9)$$

$$EER\ \left(\frac{BTU}{W\ hr}\right) = 3.41214 * COP\ \left(\frac{W}{W}\right) \quad (10)$$

$$EER\ \left(\frac{BTU}{W\ hr}\right) = 3.41214 * 0.056 = 0.19\ \left(\frac{BTU}{W\ hr}\right) \quad (11)$$

We converted our COP of 0.056 to EER in Equation (11). Our TECs independently have an EER between 2 and 3, and efficient small air-conditioners have an EER of 10-12 [35], [36], [37]. Our efficiency can be improved in several ways. First, our circulation system is working as a makeshift heat exchanger, and the difference between the efficiency of our TECs alone and our final system suggests that our "heat exchanger" is only 10% effective. Additionally, if instead of running 2 TECs at 8A, we run 4 TECs at 4A, we can double the efficiency of our TECs [14]. Finally, the efficiency may be improved by adjusting the flow rate of the water. We used the flow rate given by our pumps, but that may not be the optimal flow rate.

IV. Project Management

Table III

FPR Goal	Status
Refine Complete System Functionality	
Refine data collection tool	Accomplished
Test & optimize feedback controllers	Accomplished
Refine printed circuit board	Accomplished
Refine directionality	Accomplished
Added Goals	
Graphical data presentation tool	Accomplished
Power flow analysis efficiency report	Accomplished
Battery gauge	Accomplished

Table 3. FPR Deliverables.

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

In progressing to our final design review, our team made significant accomplishments by demonstrating full functionality through system refinement. Our project continually increased in difficulty as the academic year progressed. Team management pushed us beyond the required workload by adding a computing block, switching system, cable management system, efficiency analysis, relocation of hardware to the bottom of the unit, and painting of the system

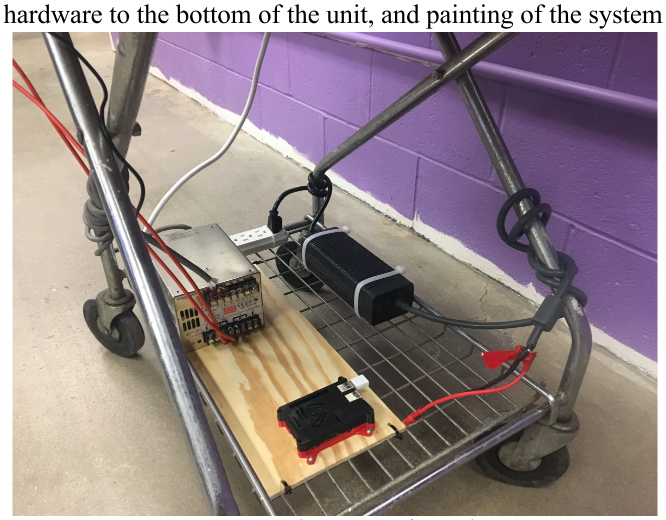

Figure 12. Relocation of Hardware.

for demo day curb appeal. Further, our evaluators added features during design reviews. Given our project's initial research-like objective of energy storage already being ambitious, combined with the plethora of added functionality over the course of the year, our project's successful completion was very challenging to manage. Notwithstanding, our team successfully finished due to passionate engineering and management on top of extreme input of work hours. Shira Epstein, Director of Campus Makerspaces, observed overall that senior teams struggle to collectively work in the same location simultaneously. However, she noted our team, whilst being the largest, productively worked in the same locations at the same times each week.

Table IV

	PDR	MDR	CDR	FPR	Total
School	$0.00	$303.72	$164.20	$106.40	**$574.32**
Jayme	$0.00	$35.05	$211.01	$372.47	**$618.53**
Jason	$0.00	$20.00	$74.58	$0.00	**$94.58**
Total	**$0.00**	**$358.77**	**$449.79**	**$478.87**	**$1287.43**

Table 4. Table of Expenses.

Each team member contributed individual expertise derived from their experiences and relevant coursework. Most of the relevant coursework had 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 helped in designing our control and feedback subsystems. In Spring 2019, Ajey enrolled in MIE 570, Solar & Direct Energy Conversion, helping us characterize and model our system to run off photovoltaic panels. Jason and Richard enrolled in ECE 547, Security Engineering. ECE 547 taught about the increase in attack vectors associated with wireless connectivity. Jason and

Table V

Device	Quantity	Cost for 1 Unit	Cost For 1000 Units
12V DC Power Supply	1	$20	$20
24V DC Power Supply	1	$35	$30
ATmega328	1	$1.96	$1.62
Closed Loop Coolers	2	$75	$75
Enclosure	1	$25	$25
Insulation	11.2 $ft.^2$	$6	$3
Thermocouple	1	$8	$5
PCB	1	$27	$13
PC High Volume Fan	1	$12	$8
Pump	2	$12	$9
Raspberry PI	1	$30	$22
TEC	2	$150	$138
Tubing	15 ft.	$3	$1.50
Total	-	**$404**	**$351**

Table 5. Table of Development & Production Costs.

Richard decided our IoT connectivity would be limited to data exporting and not system control. If system control was to be implemented wirelessly or through the smart grid, encryption algorithms would need to be investigated and implemented onto our system to ensure the risk of attack is minimized. These courses provided 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 was useful for data collection. Jayme has previous leadership experience, leading the team to choose him to also have a project management role. Jayme designed the team website and managed project documentation. Ajey is naturally comfortable with public relations, leading him to also take a communications role. Ajey and Nicholas have built experience in thermodynamics over the academic year. Richard reviewed literature for heat transfer analysis. Ajey and Nicholas have experience in MATLAB programming. Ajey and Nicholas have 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 met several times a week and maintained real-time communication. The team worked by holding regular building sessions where team members discussed challenges with their assigned tasks, receiving peer input and guidance. Team building sessions provided a motivated environment to finish delegated tasks. These sessions had been productive. Our project tasks were assigned and tracked using Gantt charts. Tasks were delegated and balanced based on individual expertise and interest level.

V. Future Work

Future work on our project would require consultation with mechanical engineers and increased funding to further research and development. Mechanical engineering would be needed to experiment with flow rate, use of heat exchangers and water loops. Flow rate should be varied and experimented with to find the optimal rate at which cooling effectively transfers to the liquid solution. Heat exchangers would be an improvement over the implemented radiator blocks. Water loops would increase the surface area that chilled air passes over. Water loops should be made of a material that maintains a cold temperature. Increased funding would allow for higher quality sensors, professional cable management system, solar integration, more TECs at lower currents, and demand-side management (using IoT input from grid administrators of real-time grid load and power pricing) to schedule when our system runs. We exceeded system specifications without formal education in mechanical engineering and limited funding.

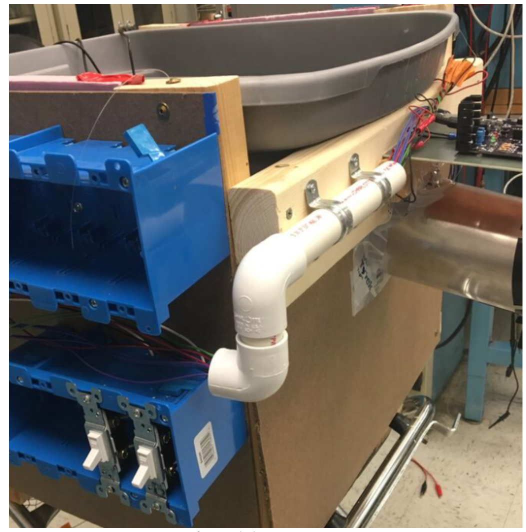

Figure 13. View of Cable Management in progress.

Figure 14. View of finalized Cable Management.

VI. Conclusion

Table VI

Requirement	Specification	Value	Actual
portable	dry weight	< 150 lb	60 lb
	size	< 20 cuft	20.8 cuft
cooling	air cooling	3.5ºF	3.9ºF
responsive	water cooling	< 6 hours	3 hours

Table 6. List of system results.

The concluding state of the Solar Winds senior project is a cooling system that stores electrical power as thermal energy to deliver directional cooling. We arrived at this final point by working together as an organized team of 5 electrical engineering seniors. During the yearlong building process, we had frequent meetings and building sessions. We completed our system by implementing the cooling, control, sensors, tracking, power and computing subsystems. Our team experienced difficulties during the research and development process. To overcome such difficulties, we investigated design alternatives, objectively examining whether these alternatives contributed towards or detracted from reaching an effective energy storage cooling solution. We verified our system's final performance and satisfaction of project specifications. With hard work and perseverance through problems often outside our electrical expertise, we successfully completed our senior undergraduate capstone experience by delivering a project with potential to positively impact the international energy industry.

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