

Solar-Powered Refrigerator on Wheels: An Engineering Design Challenge

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Abstract — According to the Environmental Protection Agency, the agriculture industry in the United States accounts for 11% of total greenhouse gas emissions. Some of these emissions are due to the refrigeration and transportation needs of agricultural products; therefore, it would be beneficial to utilize renewable energy for these functions. This study focuses on the design and implementation of a solar-powered mobile cooling unit to power refrigerated storage and transportation units, specifically for small-scale farming. To inform the design process, small-scale farmers were engaged as potential stakeholders to learn about their current practices and opportunities to create value for them with a mobile cooling unit. A series of experiments were conducted to understand the performance capabilities of the Internal Cooling System and the Solar Battery System. Temperature studies were run to ensure that desirable temperatures could be achieved and maintained within the unit. These were conducted in different weather conditions to quantify external impacts. It was shown that desired temperatures could be achieved and maintained, and that a solar-powered system would be able to serve as the power source for a mobile cooling unit.

I. INTRODUCTION

In 2018, the EPA stated that U.S. agriculture contributed 11% of greenhouse gas emissions [1]. However, agriculture includes more than the production of crops and raising of livestock. The farming and agriculture sector also rely heavily on transportation for products to go from “the farm to table,” as well as electricity production and infrastructure to store and refrigerate foods [2]. Combining these areas of greenhouse emissions, the farming industry in the U.S. is a significant contributor to climate change. Since transportation of agricultural products often relies on temperature-control, additional emissions are possible “because of the extra fuel requirements for cooling and because of leakage of refrigerant” [3]. Greenhouse gas emissions can be as high as 40% of automobile emissions due to the conventional use of diesel engine vapor compression refrigeration systems [3]. Refrigeration is a requirement for agriculture standards to ensure food quality, longevity, and safety, however the majority of the refrigeration systems are impacting the environment.

To help address the need for environmentally conscious, large-scale, mobile refrigeration, studies have been conducted to identify the feasibility and benefits of converting fossil fuel power to solar-power. The focus of the studies was powering refrigerated units for transportation using photovoltaic solar-power instead of a

diesel generator [4,5]. The studies have shown the economic benefits, greenhouse gas emission decreases, and possibility of this technology working for large-scale transportation [4,5]. Both studies also concluded the solar-powered unit had the highest functionality in sunny and cooler climates. One study emphasized the energy generation dependence on “ambient temperature and the level of irradiance or sunlight available” [4]. When the unit was stationary, a higher thermal load was present, therefore increasing the heat transferring to the surrounding environment, including the inside of the trailer, which could cause internal cooling problems if left sitting for long periods of time with high solar radiation [4]. However, during unusually high temperatures, the unit was still able to operate and meet the daily deliverables of cooling temperatures throughout the testing operation [4]. Another study concluded that while there are technical challenges to create a solar-powered unit, it is feasible [5]. Two main benefits of this unit included a decrease in pollution from a diesel generator to solar-power and long-term cost reduction [5]. A design challenge with the battery system impacted the internal refrigeration system. The problem was fixed by altering the design while keeping the material being used and heat transfer as a key consideration in the internal configuration [5].

There is a gap in knowledge and research on small-scale farming industries, especially in the United States, and how they refrigerate, store, and transport crops. Also, the harvesting, refrigerated storing, transporting, and selling of agricultural products are often handled separately. Therefore, there is an opportunity to create value for small-scale farm operations by connecting these actions. Most trailer units are diesel-powered and are only specific to large-scale transportation. There are only a few studies looking into renewable energy power sources.

USDA’s Good Agricultural Practices (GAP) certification is a “voluntary certification program which verifies through an audit that sound food safety practices are being used” [6]. By having this certification, a farm has been inspected for post-harvest sanitation practices, safety of the growing and harvesting of fruits, vegetables, and nuts, and other proper farming practices. Increasing the availability for small-scale farming to achieve GAP certification “is an essential step toward tapping the market opportunities for sustainably-grown fruits and vegetables in today’s changing local food production and distribution system” [7].

This project aims to explore the feasibility of configuring and creating a solar-powered mobile cooling unit for small-scale, local farmers. The goal is to generate a model for small farmers to replicate to help them meet USDA and GAP regulations. This paper focuses on the design and testing of the internal cooling system.

II. PROCEDURE

A. Survey

A user-centered design process was employed. The first step in the process was to engage local small-scale farmers as project stakeholders to learn more about the experiences and needs of small-scale farmers in our area. A survey was created and distributed to local farmers through the NC Cooperative Extension. Survey questions included, but were not limited to asking what they produce, if they transport their agricultural products, and whether the quality, diversity, and volume of their agricultural products might be improved with more accessible refrigeration.

B. Internal Cooling System

The Internal Cooling System consists of a box AC unit, CoolBot® Walk-In Cooler Controller, and installed rigid foam insulation inside the mobile cooling unit. A CoolBot is a device that uses sensors to control the airflow and temperature of a box AC unit. It works similarly to a thermostat where the user sets the CoolBot to the desired temperature of a space, and the CoolBot works with the air conditioner to control the temperature of the space [8]. The Internal Cooling System was constructed using the CoolBot Trailer Construction Guide for a 6ftx10ft trailer [8]. R25 Polyisocyanurate rigid foam board insulation panels, donated by a local wholesale building material company specializing in high-quality polyiso insulation products, a GE® ENERGY STAR® Air Conditioner, and non-fiberglass reinforced plastic panels (NRP®) were installed, transforming the trailer into an energy-efficient cooler.

To test the Internal Cooling System, six Go Direct® Weather System Vernier test probes were used inside the trailer to gather temperature data. For the initial testing in the fall, five of the probes were placed at different locations within the trailer to gather information at key points, such as near doors, the ceiling, and floor. The sixth probe was stationed with the CoolBot temperature sensor probe, to allow for comparison between the set temperature of the CoolBot and Vernier probe temperature reading. In the spring, one of the six probes was moved outside of the unit to collect external climate conditions at the same time as the rest of the data collection. This proved to be beneficial in overall data analysis of the spring temperature study data with having the same time step for outside conditions.

C. Solar Battery System

The Solar Battery System consists of the solar panels, a solar charge controller, batteries, and an inverter to ultimately power the Internal Cooling System. Two

options were considered to create the Solar Battery System: a custom build and a solar generator system.

A custom build, as shown in Figure 1, allows users to hand select each piece of the Solar Battery System, making it possible to choose the system components directly aligned with the power necessary for the Internal Cooling System in the mobile cooling unit. This build is very user-focused, with the builder choosing the type and rating each piece of equipment to work with each other. In addition, this route is cheaper as the total cost of the system components is less than most solar generators and panels. However, this option can be difficult due to inconsistencies with products from different suppliers, and the need for proper equipment or knowledge of the inner workings of the system components.

To establish the design parameters, the first calculation steps included finding the total power needed and daily energy usage for the mobile cooling unit. The AC Unit was rated at 995W, and adding the CoolBot into that system, it was estimated that the rated total power need was 1000W. It was then determined that the runtime of the AC unit would be 10 hours, as this value is directly related to peak sun hours, the time of most direct sunlight daily [9]. Thus, 10 hours was used as an estimate to account for running the AC unit during warmer, longer summer days. The daily energy usage was determined by multiplying the total power need by the daily runtime, which resulted in a maximum of 10 kWhr per day in warmer seasons.

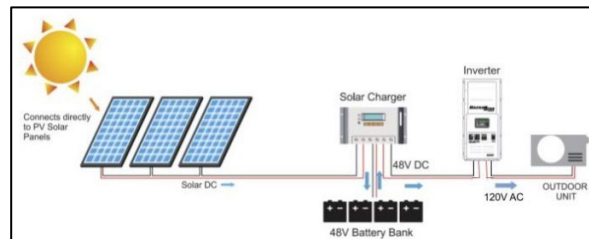


Figure 1. Schematic of a custom-built solar battery system

The second option is a solar generator set-up. A solar generator is an electrical device that combines a charge controller, batteries, and inverter all into one system, paired with solar panels to recharge the unit, see Figure 2 [10]. These units are very popular for off-grid living, RV travel, and camping, as well as for home battery back-up storage in case of power outages; therefore, generators are a reliable source of power for a mobile cooling unit system. However, solar generator units are very expensive as they combine all of the main solar battery components into one system. Also, depending on the power need of a system, the solar generator dictates every piece creating the power for the devices. There is no flexibility to alter system components or scale the system for the specific power requirements of the Internal Cooling System.



Figure 2. Schematic of a solar generator system

Because it would be counterproductive to store heat-releasing equipment inside of a refrigerated system, it made the most sense to house the electrical equipment in a box on the trailer hitch, under the AC unit. In addition, the trailer is relatively small inside and it would be more efficient to maximize the inside space for crops.

III. RESULTS AND DISCUSSION

A. Survey Results

Eight of the ten survey participants fully completed the survey questions, with seven of the ten farms being over 15 acres and three of the ten farms only producing fruits and vegetables. The results showed that of these farms, six of nine sell their agricultural products and seven of the nine have a need to transport their products. Currently, five use passive cooling and four use non-cooling methods, like ice chests or storage containers, respectively, with one farmer not specifying how they transport. None currently have a method of active-cooling transportation, like a mobile cooling unit or moving refrigerator. In addition, six of nine farmers have to store their products on site, with three always needing refrigeration and the other three sometimes needing it. Three questions focused on the crop quality, volume, and diversity increasing from accessible refrigeration. Of these questions, six of eight farmers reported that they would either fully benefit or benefit sometimes from accessible refrigeration on site, with only two farmers not seeing this trend at their farm. Two answered no to all questions regarding the need for refrigeration. This positive correlation showed that a mobile cooling unit could be of benefit to small farms within this region and market class (small farms with sales primarily at Farmer's Markets, CSA's, or direct to consumers), and most likely in other small farming communities with similar demographics.

B. Temperature Study

Temperature studies were conducted in both fall and spring seasons to gather information on the efficiency of the Internal Cooling System. Three sets of data were collected with the CoolBot set to 45°F (7.22°C): one 3-hr trial run to document internal versus external temperature difference (Figure 3), one 48-hr trial run to gather data over a longer period with more pronounced variations in atmospheric conditions (Figure 4), and one manual run to determine how long the Vernier software would record data consecutively (Figure 5). The 45°F (7.22°C) temperature setting corresponds to the optimal

temperature for preserving several products grown in our region, such as peppers, tomatoes, kale, rutabaga, and some melons [11]. In addition, the produce shelving areas in most grocery stores are kept at that temperature.

In Figure 3 (in the Appendix), the smooth solid line near the top of the graph corresponds to the atmospheric temperature, which was collected from Weather Underground's Greensboro, NC Weather History [12]. The smooth horizontal line near the bottom of the graph corresponds to the setting of 45°F (7.22°C) on the CoolBot controller. The remaining lines correspond to the temperatures recorded by the six temperature probes. The peaks and valleys seen in the curves for the probes are due to the air conditioning unit cycling on and off. It is clear that the probe stationed with the CoolBot temperature sensor probe does not reach the desired temperature within 3 hours; therefore, a longer trial was warranted.

Figure 4 (in the Appendix) shows temperature data collected during a 48-hour trial run. The temperature readings show a hover around the set temperature of 7.22°C, with the highest temperature reading during the cycle being 14.5°C and the lowest temperature reading 0°C at the Floor Probe. The external temperature was approximately the same as the 3-hr study, and there are trends to higher temperature during the day and lower temperatures in the evenings shown in the 48-hr study. As can also be seen in Figure 4, the Coolbot can consistently achieve the desired internal temperature, shut the air conditioner off, and turn the air conditioner back on once the internal temperature rises by about 5 degrees during a 48-hour trial run.

As previously mentioned, the spring study used a probe outside of the unit to collect data in time with the rest of the probes, as shown by the dark yellow line in both spring data sets. The 3-hr spring temperature data is shown in Figure 6 (in the Appendix). The CoolBot was once again set to 45°F (7.22°C), with inside temperatures ranging from a minimum of 4.3°C to a maximum of 22.9°C, and external temperatures ranging from 24-31.3°C outside the unit during testing. The spring external temperature was greater than the fall's maximum recorded temperature of 23.33°C. Like the fall temperature study, it takes the Internal Cooling System over 1.5 hours to start hovering the CoolBot set temperature, showing that longer studies can better determine how accurate the Internal Cooling System can function.

When trying to replicate the 48-hr temperature study in the spring, issues arose with the computer used to collect the data. To solve this problem, a shorter study was conducted that recorded for almost 11 hours, shown in Figure 7 (in the Appendix). Unlike the 3-hr spring study, this trial was started when the AC unit was already running and did not have the same lag time as other trials to decrease internal temperature. Like the fall 48-hr study, the Internal Cooling System hovered around the CoolBot's set temperature for the duration. In addition, the small internal spike at around 7 hours shows when the trailer was opened to check the status of the study,

indicating that further analysis would be warranted to record how fast the internal temperature recovers after allowing cool air to leave the unit.

In addition, a 32°F (0°C) trial was conducted for 11 hours, and this study is shown in the Appendix (Figure 8). Since both the 3-hr fall and spring temperature studies demonstrated that it takes time for the Internal Cooling to start stabilizing, it was run for a longer period of time in order to better analyze the accuracy of the unit reaching freezing temperatures. As shown, the internal temperature did not reach the set temperature of 32°F at any of the probes. This trial compares to previous studies as it hovered around the 5-8°C line rather than the 0°C line. This may be due to possible gaps in the trailer, allowing outside air to enter and raise the temperature.

The temperature studies showed that overall, the internal temperatures in different parts of the unit were within a couple of degrees throughout the time the AC unit was running. During longer trials, there was a higher success of the inside of the unit reaching and exceeding the set temperature. This may change with the addition of panels on sides of the trailer as that may affect the heat transfer between the inside and outside of the unit. As seen in the 3-hr studies, there was a noticeable temperature movement as the unit started at external temperatures and lowered to the CoolBot's set temperature. In the longer temperature studies, it was shown that the Internal Cooling System consistently hovered within 3-5 °C, with only the ceiling probe dipping much lower than the CoolBot set temperature. When using the temperature study with the Solar Battery System, the Internal Cooling System can be assumed to have powered down if the probe readings climb upwards, the reverse of the start of the 3-hr studies. With the change from fall to spring external temperatures, the Internal Cooling System had no issues producing internal temperatures for when the CoolBot was set to 45°F, showing that the system is successful in both warmer and cooler climates to store agricultural products requiring that temperature. However, the unit currently would not be advised to store products needing to be refrigerated at 32°F until further testing is conducted.

C. Solar Battery System

The custom Solar Battery System was chosen initially due to potential cost reduction and higher efficiency from selecting system components. The batteries were selected, based on a recommendation for a 48V off-grid battery to meet the specifications for the air conditioner. The 51.2V, 90Ah LiFePO₄ rack battery by Ampere Time allowed for easy parallel stacking of the batteries if more energy storage was needed. Based on prior success on another solar project, a WZRELB Pure Sine Wave Inverter was selected. It was also more reasonably priced in comparison to other similar products. Initially, the inverter size was selected based on the rated power need of the AC Unit and CoolBot system. However, further research revealed that the inverter power should be at least

three times the input surge current. Ultimately, an inverter rated at 3000W was purchased.

Unfortunately, several issues arose with the custom-built solar battery system which were irreconcilable within the project timeline. These included difficulty getting the inverter to work properly and obtaining a properly rated solar controller. Therefore, focus shifted to the solar generator system.

After comparing prices and power output of different generator options, the Jackery Solar Generator 2000 Pro was purchased with six SolarSaga 200W solar panels. This unit has a peak power AC output of 4400W, covering the assumption that the AC unit pulls a larger current when switching to the cool setting and 4400W is much greater than the specifications of 995W. This unit has a 2160Wh battery capacity, with a voltage of 43.2V, very close to the initial custom build battery specifications. In addition, the generator's size fits within the space constraints of the trailer's hitch, and supports pass-through charging, meaning it has a quick recharge and discharge rate. According to the Jackery website, with six 200W panels, the generator can be fully recharged in 2 hours, and a full generator can run a standard air conditioner for 2-2.5 hours. The Jackery unit was also selected due to it had a good market price compared to other vendors, very good customer service, it is based within the United States and had good customer reviews for the discharge and recharge of the generator. While this recharge to discharge rate is not at the desired efficiency for the unit, this system decreases the potential for equipment to not be rated correctly when working together and allow for an easier design and build of the battery system.

To test the updated Solar Battery System in conjunction with the Internal Cooling System, a temperature study was conducted by setting the CoolBot to 45°F (7.22°C) and running the system only on the generator connected to the solar panels. The study was set-up as a manual start and stop collection in order to gather the maximum amount of data about the internal and external conditions using only solar generated power. The first trial was run for 1.55 hours off a fully charged generator, shown in Figure 9 (in the Appendix). The goal of this trial was to test the Jackery solar generator system with the Internal Cooling System and gather initial data. As shown in the first trial, the decrease in temperature trend was the same as previous temperature studies with a non-solar power source.

A solar generator powered test was repeated to determine how long the generator would power the Internal Cooling System. Due to problems with the data collection computer, only the last 3.45 hours of the trial were recorded, shown in Figure 10 (in the Appendix). This trial started at 10:20am with full generator battery. At 2:37pm, the trial shown below started recording data. During this trial, the generator ran out of charge 2.7 hours past 2:37pm. This demonstrated that the Jackery 2000W solar generator is able to fully power the Internal Cooling System, including the data collection computer and

probes, for 6 hours and 17 minutes. This time is predicted to increase with a full solar array of 6 panels constantly powering the unit.

IV. CONCLUSIONS

Mobile cooling units would benefit the transportation, refrigeration, and storage needs of small-farming communities. Because accessible refrigeration allows for increases in crop quality, volume, and diversity, as well as meeting several standards required by GAP certification, farms that invest in a mobile cooling unit have the potential to make their operations more profitable. While these statements are primarily based on a small survey in Alamance County, NC, these assumptions can be applied to other small-farms with similar demographics and GAP certification needs. Because these units are typically generator powered, a solar-powered option is optimal to increase the mobility of the unit, as well as reduce agriculture greenhouse gas emissions.

APPENDIX

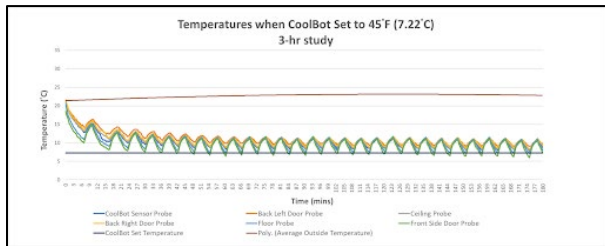


Figure 3. Fall 3-hour temperature study data

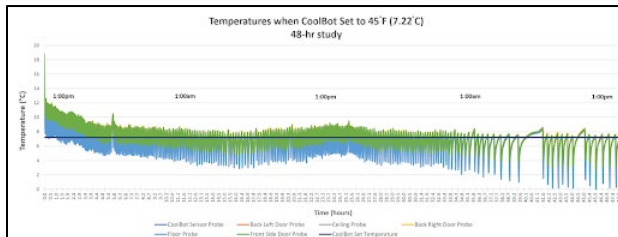


Figure 4. Fall 48-hour temperature study data

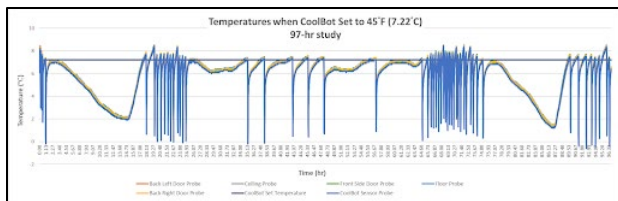


Figure 5. Fall 97-hr temperature study data

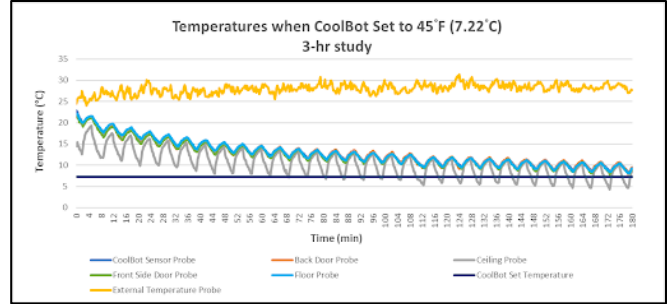


Figure 6. Spring 3-hour temperature study data

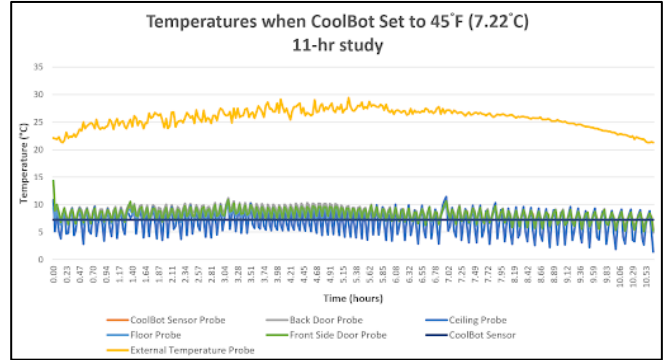


Figure 7. Spring 11-hr temperature study data

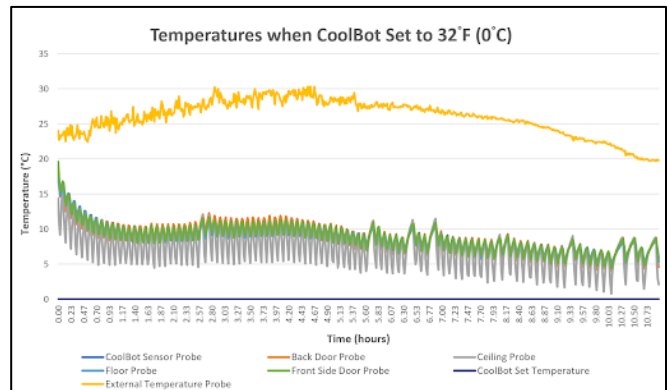


Figure 8. Spring 32°F (0°C) temperature study

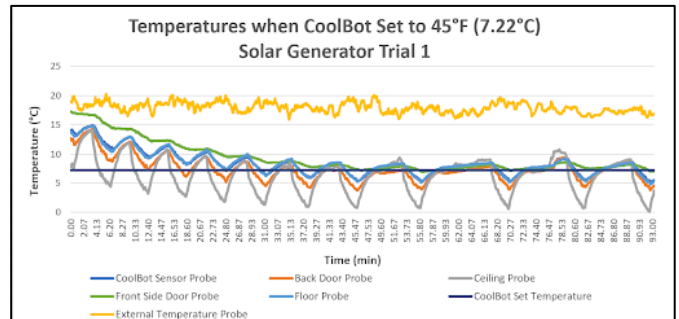


Figure 9. Solar generator trial 1

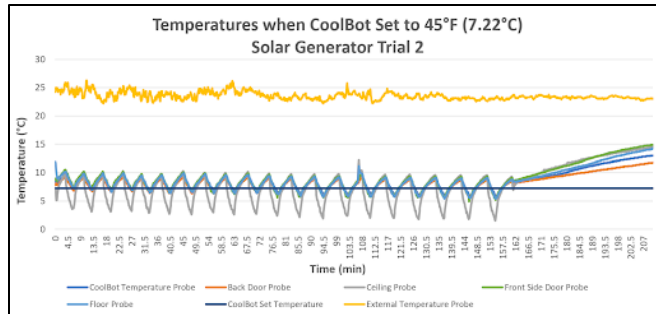


Figure 10. Solar generator trial 2

ACKNOWLEDGMENT

M. R. Poff would like to thank Dr. Sirena Hargrove-Leak, Prof. Jacob Rutz, Dr. Scott Wolter, Taylor Black, Elon University’s Honors Fellows Program and Elon University’s Lumen Prize for the continuous support throughout the project.

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