CLIMATE BATTERY

An Improved Greenhouse Climate Solution

ME 449
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Abstract

A climate battery is a geothermal tubing system installed under a greenhouse into which one pumps ambient greenhouse air. The airflow causes a heat transfer between the air and ground and, using the typically colder subsurface earth as a heat storage mechanism, one can effectively create a “battery” in which heat is stored underground and pumped back into the greenhouse proper during colder temperatures, usually on a day-night cycle. While climate batteries are not a new system, there is little to no published research on the best way to construct and operate this technology. The goal of this project is to collect and analyze data from the existing climate batteries at Threefold Farm in order to make recommendations on how to improve the design and predict the capabilities of future climate batteries..

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Acknowledgements

We would like to thank Tim Clymer and Threefold Farm for sponsoring this project and letting us dig up his greenhouses, as well as Dr. Brian Maicke for sharing his knowledge and experience to help guide us toward a successful project.

Chapter 1: Introduction

This project got its start when Tim Clymer from Threefold Farm delivered a presentation on what a climate battery is, how they are being used at Threefold Farm, and that he would like to learn more about the actual properties of how and why they work. The ultimate goal was to not only produce a more effective and more efficient climate battery, but for Threefold Farm to become a reference and source of information for other growers looking to use this technology.

The nature of the project strayed from the typical design-build approach to Capstone projects, as shortly after the initial presentation, there were two functioning system already in place at the farm, and building a third was far outside the budgetary scope and timeline of the project. However, it was handled in the same way, as the design process involved creating an effective sensor layout to record temperature data on the performance of the systems and potential modifications were simulated and calculated for effectiveness, and those that could be tested were implemented. While a climate battery was not built as a part of this project, the information and analysis was used to make recommendations for improvements of future systems and can serve as a starting point for future Capstone teams to dive deeper into the performance and optimization of a climate battery.

Chapter 1 will continue with describing the purpose and use of a climate battery, as well as other methods, then Chapter 2 will detail the two systems in place at Threefold Farm. From there, Chapter 3 covers the study points, how they were studied, and the results of those studies before making recommendations for future systems in Chapter 4. Chapter 5 consists of project documentation like a responsibility matrix, schedules, and budget, then the conclusion will take place in Chapter 6.

Problem Statement

One of the main advantages to growing plants in a greenhouse is that it protects them from most of the outside elements, namely temperature and wind. It provides a sheltered space to grow crops outside of their regular seasons, which can be to increase their yield later through the year, or to start their growth earlier, both of which can improve productivity and increase profits. Cold outside temperatures make for cold inside temperatures too, but a greenhouse can be heated, whereas an outdoor garden cannot. Greenhouses also pose a potential problem in the summer, where high outside temperatures are further increased by the enclosed space, and those elevated temperatures can damage and kill plants, just like low temperatures, which is the main concern of growers. Most heating solutions have a high energy and environmental cost or are detrimental to the conditions inside the greenhouse.

Solutions

Existing Solutions

There are several existing solutions for climate control in greenhouses; however, they each have their own drawbacks that leave something to be desired.

The simplest and most common solution is a heater to maintain warmer temperatures. Adding a thermostat allows for precise temperature regulation, and as long as the heater has enough capacity to overcome the outside temperature, any climate can be maintained. While electrical or fuel-fired heaters are extremely effective in providing the climates necessary to overwinter crops, they are heavily fossil fuel dependent, expensive to run, and decrease the humidity in the greenhouse.

Thermal masses are a simple method of retaining heat by using large quantities of stone, brick, or water to retain heat inside the greenhouse. The thermal properties of the masses help to keep the greenhouse warm at night by slowly dissipating the energy they absorbed from the sun during the day. This method has no environmental impact and inexpensive, but it requires a relatively large amount of space inside the greenhouse and is weather dependent for the benefits it offers in return.

Insulation is an exceptionally effective way to retain heat, but is by no means a way to heat a greenhouse, as it generates no heat by itself. It could be used to increase the efficiency of another solution by slowing the rate that energy is lost to the outside, but is ineffective by itself. Depending on the type and installation, it can also reduce the amount of sunlight entering the greenhouse. In the off seasons, when the sun is less powerful already, further reducing the amount that reaches the plants makes it more difficult for continued growth.

Using compost or manure inside a greenhouse is a common practice to enrich the soil to improve growth, and as that material decomposes, it produces a considerable amount of heat. It is renewable, resourceful, and multipurpose, and possibly being done already. However, this method also requires constant upkeep and replenishment, and is not easily temperature controlled.

A climate battery is a geothermal system, where air is forced underground through a series of tubes before reentering the greenhouse. During the day, when the air is warm, the heat is transferred from the air to the soil which results in warmer ground temperatures. At night when the air in the greenhouse is cool, when it passes through the warmer ground, it heats up and increases the temperature in the greenhouse.

Solution Requirements

Greenhouse heating needs are dependent on the type of crops being planted, the amount of season extension needed, and the climate zone that the greenhouse is in. For Threefold Farm, the main crops in the greenhouses were figs and tomatoes. The solution must extend the growing season by three months and be able to keep the interior temperature above 20°F to prevent damage to the fig plants. Ideally, it would be able to keep the temperature above 35°F to prevent hibernation of the figs and keep the roots from freezing and allow for a year-round growing season.

Solution Criteria and Screening

Each existing solution was scored based on a set of weighted factors with a 1 being the least desirable and a 5 as the most desirable to compare each method numerically systematically. The factors were Cost, Space, Environmental Impact, Heat Flow Method, and Greenhouse Conditions. The results are shown below in Table 1.

Cost was weighted at 20% because a more expensive system is not ideal, but an effective system can increase profits during the winter or increase the rate of return at the beginning of the season by allowing for earlier growing starts. Installation Costs are one-time costs including labor and materials to install the system, and Running Costs are the costs to upkeep and maintain the system. They were scored separately due to the lack or correlation between the two factors.

Space is the amount of usable area for crops consumed by the system in the greenhouse, and carries the highest weight at 30% because the purpose of a greenhouse is to grow plants, which cannot be fully accomplished if a heating system is taking up large amounts of floor space.

Environmental Impact is the cost of operating the system on the environment. It was weighted at 15% because in a business operation, the greenhouse needs to stay warm, and fuel or electric is simply a cost to do business.

Heat Flow Method compares how effectively a system generates or retains heat. Heat Flow Method is weighted at 15% because active heat generation is preferred over retention, but as long as the greenhouse stays warm, the method does not matter.

Lastly, Greenhouse Conditions contains effects of the system on the humidity in the greenhouse and the amount of sunlight entering the greenhouse. They are weighted at 20% because the less disturbance there is to the conditions, the better the plants will grow.

	Weight	Heaters	Thermal Masses	Insulation	Compost	Climate Battery
Cost	0.20					
Installation		3	4	4	4	1
Running Costs		1	5	5	3	4
Space	0.30	4	1	4	2	5
Environmental Impact	0.15	1	5	5	4	4
Heat Flow Method	0.15	5	2	1	3	4
Greenhouse Conditions	0.20					
Humidity		1	5	5	4	5
Sunlight		5	5	1	5	5
Total	1.00	4.1	5.15	5.1	4.85	5.7

Table 1: Selection Matrix

Concept Selection

The climate battery is the highest scoring concept by a fair margin, with the only substantial negative aspect of the system being the high installation costs. However, it takes up minimal space in the greenhouse, only requires a small amount of electricity to run the fans, is able to actively store and retrieve thermal energy, and does not affect the growing condition in the greenhouse. The thermal masses and insulation had the next highest scores because both are low cost and have little environmental impact, but are only able to retain heat already in the greenhouse. Compost has moderate running costs in maintaining the decomposition and takes up space in the greenhouse which contributed to the lower score. Lastly, heaters had the lowest score because they are expensive to run, have a substantial environmental impact, and tend to dry out the air in the greenhouse.

Chapter 2: Climate Battery Designs

The climate battery was the highest scoring option in the selection matrix, but even if it had scored lower, it would have still been the focus of this project, as Threefold Farm has two climate battery systems installed and functioning, the Gray House and the Blue House.

As previously mentioned, a climate battery is a geothermal system, using air forced through buried tubes as the medium for heat transfer to and from the soil. The longer the tubes and the larger the quantity, the more contact there is with the ground and therefore more heat transfer as well. In order to push air through multiple tubes with a single fan, both ends of the tubes are connected to a larger diameter manifold that is buried at the same depth. In order to get the air to and from the manifolds, they are connected to vertical risers that go to or above ground level. A fan is placed in one riser, the inlet, to force the air through the tubes and it comes back up out of the other riser, known as the outlet or exhaust. A diagram is shown below in Figure 1.

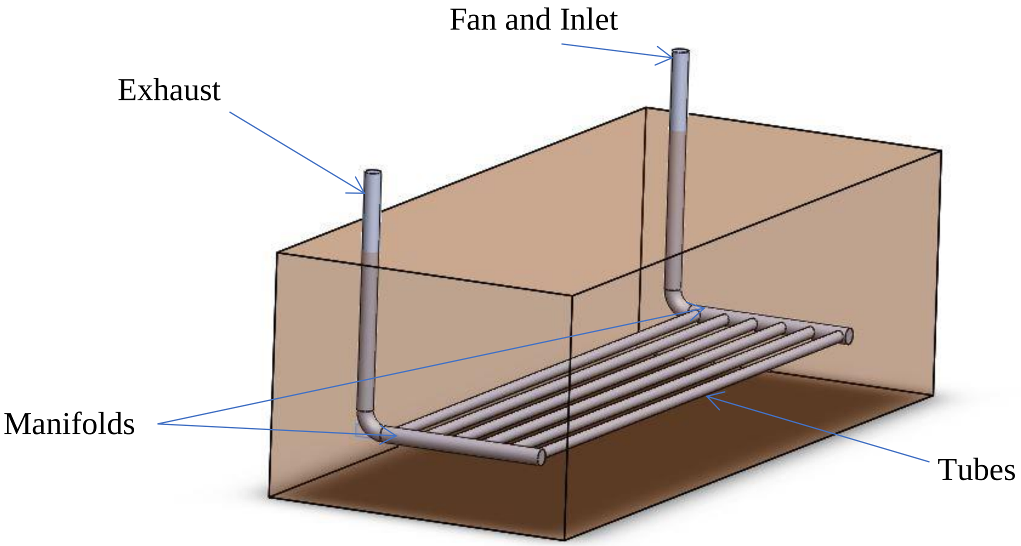


Figure 1: Climate battery diagram

The fans are controlled by a thermostat with two set points, one set to turn on the fans for cooling mode, and one for heating mode. Cooling mode most commonly occurs during the day, when the greenhouse is air is warmer than the ground temperature, charging the battery. This is an advantage to the greenhouse during periods of high temperatures, as the system works as an air conditioner and reduces the overall temperature inside. Heating mode is when the heat stored in the ground is retrieved through the colder greenhouse air to increase the temperature inside the greenhouse.

The Gray House

The Gray House is the first climate battery installed at Threefold Farm in late 2017, with a model shown in Figure 2. It consists of three sets of fans and manifolds in a 26’ x 88’ footprint inside of the 30’ x 96’ gothic style greenhouse. The greenhouse is double walled, which means there are two layers of plastic separated by an air gap to help insulate the structure. A 20” fan capable of pushing 5,000 CFM through the tubing powers each individual system. The tubes are 4” socked corrugated perforated drain tubing, and there are approximately 47 tubing runs of 30’ diagonally connecting each manifold. Total, there is 4,250 feet of tubing, buried between 2’ and 4’ below grade in the soil. The manifolds are 20’ long, 18” twin wall drain pipe, and the risers are slightly larger at 24”. Rigid foam board insulation was installed around the exterior of the battery. The entire system was able to maintain above 20°F during the 2017-2018 winter, and costs around $500 per year to run.

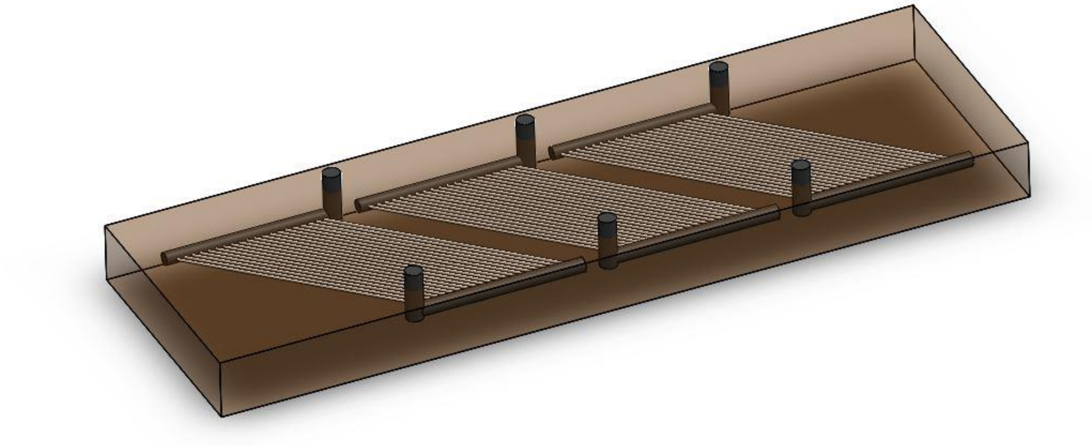


Figure 2: Gray House climate battery

The Blue House

The Blue House was finished in Fall 2018 and has the same concept as the Gray House, but some substantial design changes, shown in Figure 3. It is a 34’ x 96’ gothic structure but is single walled, and the battery consists of 12 individual systems in a 21’ x 84’ footprint. Six systems are at 3’ below grade, and the other six are at 6’ below grade, each powered by a 425 CFM 6” inline duct fan. Small booster fans were placed in the exhaust risers to help compensate for the smaller capacity of the fans. The system uses the same 4” tubing, with six runs of 41.6’ per manifold in the upper systems, and seven runs in the lower systems for a total of 3,250’ of tubing. Each layer of tubes is backfilled with stone. The manifolds are 6’ long; they and the risers are made from 6” DWV pipe. There is no insulation around the battery. The Blue House should also cost around $500 per year to run.

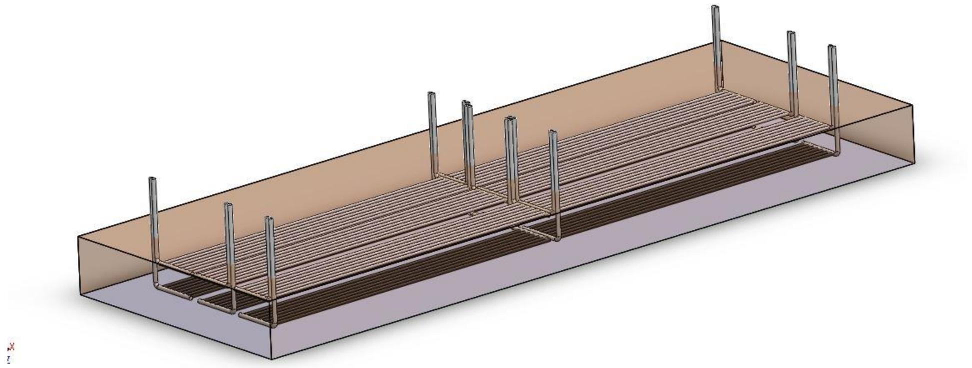


Figure 3: Blue House climate battery

Chapter 3: Study Points

In order to make recommendations and improvements on two already built designs, data would need to be collected from the Gray and Blue Houses to determine how each was performing. The focus was on temperature, both in the greenhouse and in the ground, but thermostat set points and humidity are also factors that affect performance. Airflow was another important focus, as it is the movement of air in the tubes that is the main method of heat transfer. This was studied in fan size and speed, manifold design, and the use of booster fans.

Greenhouse Conditions

Temperature Data Collection

In order to analyze and evaluate the climate batteries, soil temperature, air temperature, and humidity readings were collected from inside and outside the greenhouses in order to form an accurate understanding of the heat transfer and capabilities of the systems. Two distinct models of sensors were used for data collection, Elitech RC-4, and Elitech RC-4HC. The sensors are programmable to record at a set interval and stored in its memory. Some of the RC-4 sensors were connected to a probe and used to collect soil temperature data, and those without a probe were used to collect air temperature data. A small number of the RC-4HC sensors were purchased because they also record humidity data. The sensors were all set to record every 15 minutes, and data was collected and compiled weekly throughout the course of the project.

The probes that came with the sensors were not long enough to reach the desired depths, so an extension wire was spliced in, with the solder joints protected by heat shrink tubing. Before installation, all of the sensors with extended probes were calibrated after reaching steady state in a bucket of soil. The probes were fed through a piece of conduit for protection, with the deep probe protruding from the bottom and the shallow probe protruding from the side. The conduits were installed in holes dug in the greenhouse, and the sensors secured to the conduit.

An array of ground temperature sensors was buried at 3’ and 5’ below grade at opposite exterior corners, opposite interior corners, centered at the middle, and centered approximately one-quarter of the way through each greenhouse. These locations were labeled ‘A’ through ‘L,’ and each sensor was labeled with an ‘S’ for shallow or a ‘D’ for deep. Air sensors were placed approximately above each interior ground sensor at 6.5’ above grade, with two additional sensors in the center of each greenhouse, one 1’ above grade, and one 15’ above grade. Two sensors per house also recorded humidity data. These air sensors were labeled ‘A2’ through ‘A13.’ Air sensor ‘A1’ was placed underneath a porch roof near both greenhouses to record outside air temperature and humidity. Air sensors ‘R1’ through ‘R6’ were placed in the inlet and outlet of a system in each greenhouse. As different tests or modifications were implemented, sensors were moved around in order to collect the data that seemed most important. Figure 4 shows the initial and final sensor layouts in the Gray House, and Figure 5 shows the same information for the Blue House.

While the ideal scenario is to have a grid of sensors at multiple depths and heights, it is impractical and expensive, so it was assumed that the temperature distribution is symmetric across the short side of the greenhouse, as well as in the back half.

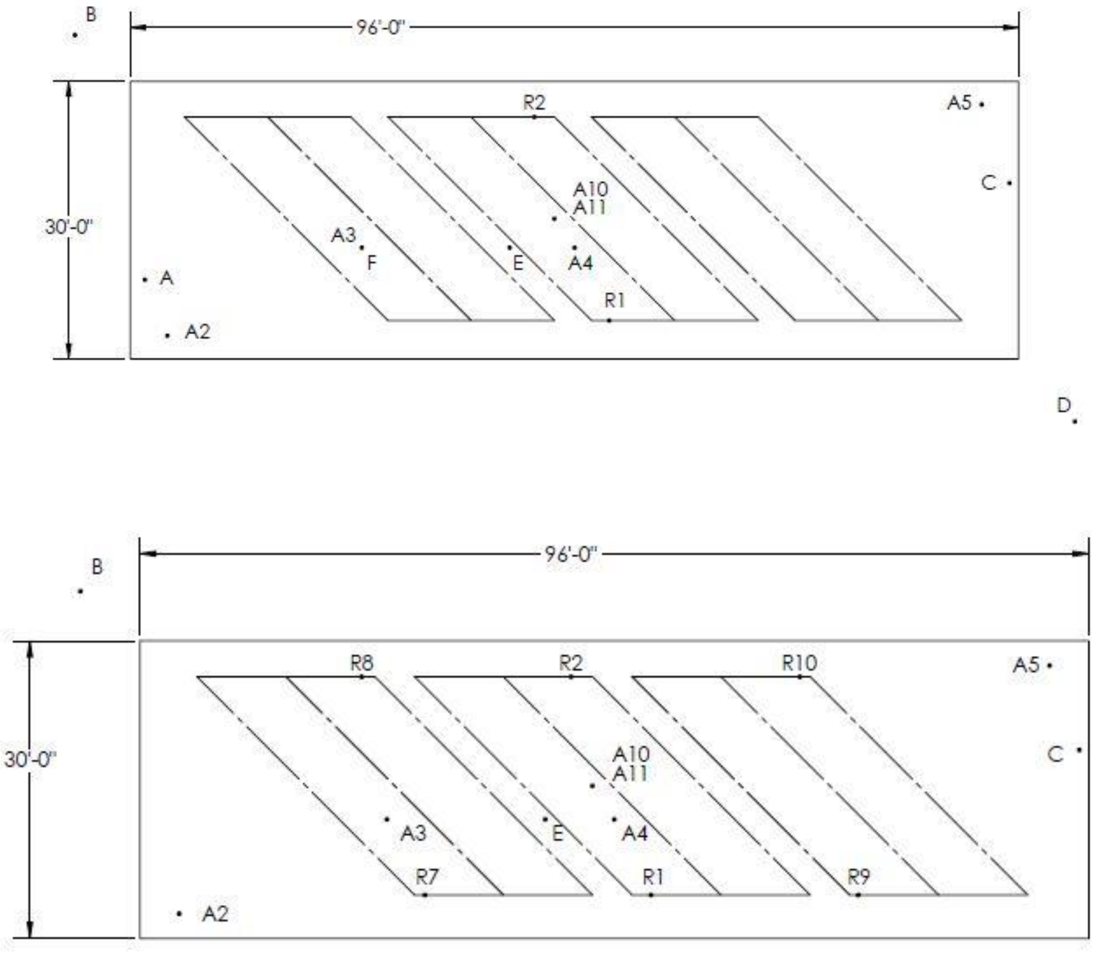


Figure 4: Gray House initial, top, and final, bottom, sensor layouts

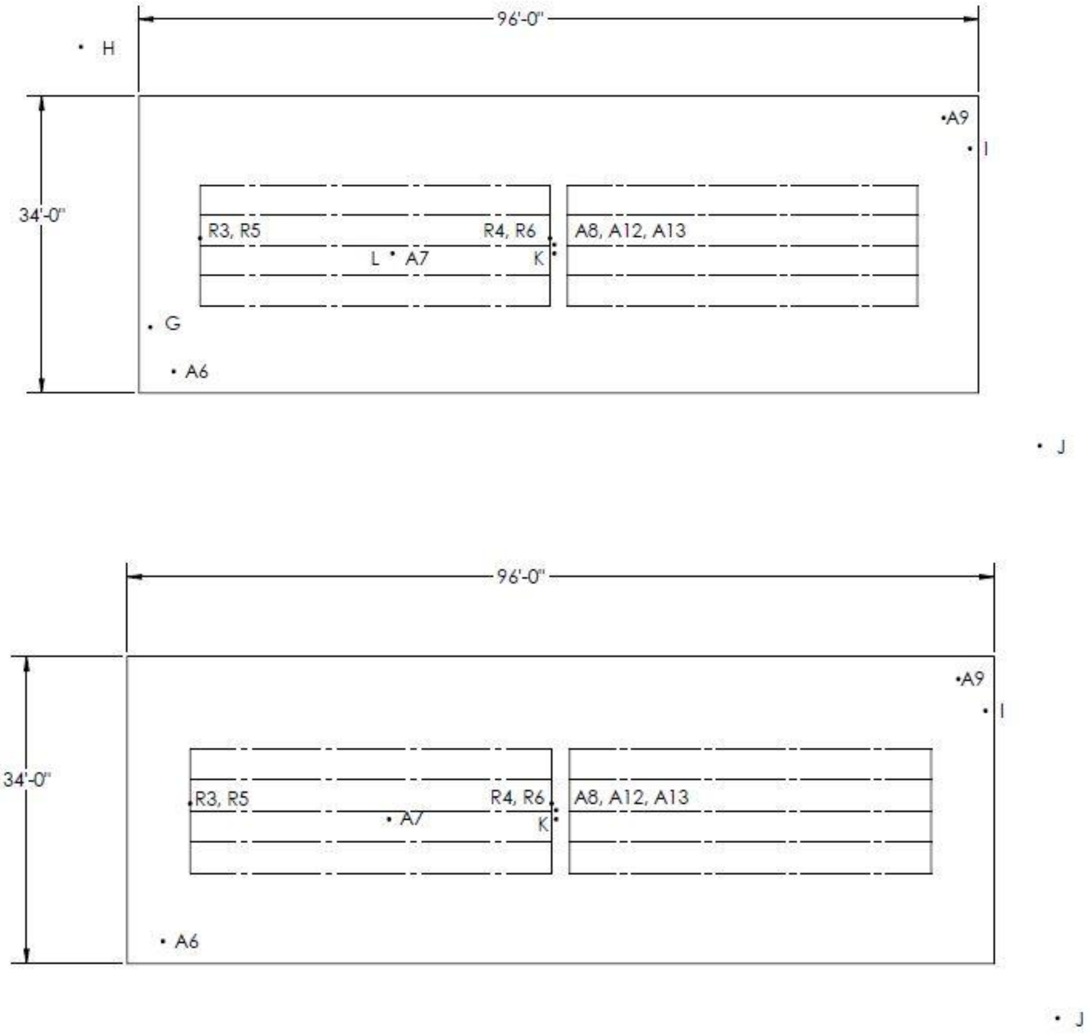


Figure 5: Blue House initial, top, and final, bottom, sensor layouts

Temperature Analysis

Data from the forty-four sensors installed in and around the climate batteries was collected for twenty-four weeks starting in November 2018 and concluding in April 2019. One of the first uses of the data was to understand how much warmer the air inside a greenhouse is compared to the air outside. The Gray and Blue Houses are graphed against the outside temperature throughout the course of the study in Figure 6. At both the beginning and end of data collection the greenhouse was open to allow outside air to flow in and out of the greenhouses. After Week 1, the sides and doors were kept closed to allow the greenhouse to build heat during sunny days as the weather transitioned to cooler days with less sunlight. After averaging the data from air sensors in each greenhouse, in comparison to the shielded outside air sensor, the Blue House with one layer of plastic made around a 15° F temperature difference, while the two layers and air gap of the Gray House made around a 20° F temperature difference.

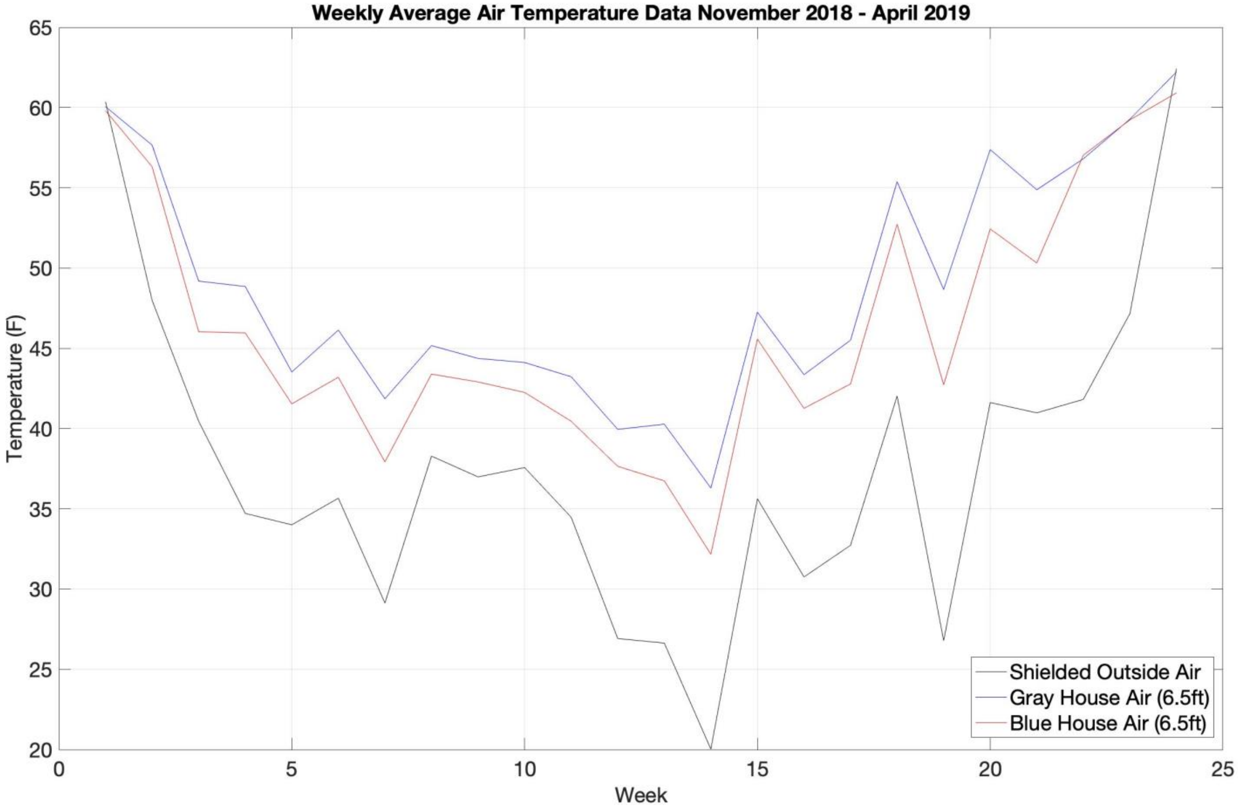


Figure 6: Outside air temperature vs Gray House vs Blue House

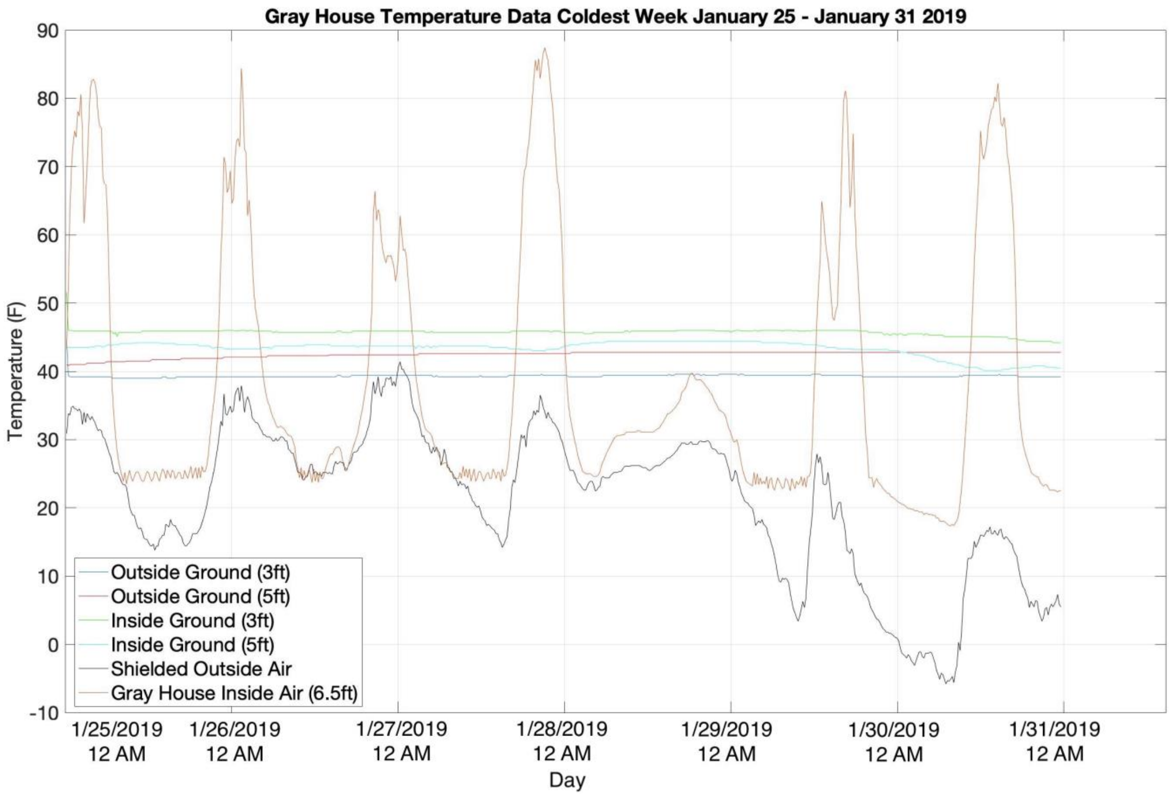
Another use was to take the data and use it to determine how effective the current systems were. Initially, psychrometric charts, which use air temperature and percent humidity to determine the enthalpy in BTUs per pound of air, were used to verify the idea. However, to analyze the data effectively an Excel add-in called “Get-Psyched” was used. The add-in allowed Excel to calculate enthalpy, given that air temperature, pressure, and humidity are known. To use this to determine the total system heat transfer, the pressure, humidity, and change in temperature from the outlet to inlet (when the systems were running) were used. Once the change in enthalpy was known, the air density was calculated. Using the density and the volumetric flow rate of the system fans, the mass flow rate of each system was determined. With the mass flow rate and the change in enthalpy per pound of air determined, the total heat transfer per system could then be calculated. The next step was to determine how efficient the systems were at transferring heat; the temperature data measured by the centrally located ground sensors were subtracted by the inlet air temp for the system, and then divided by the system outlet subtracted from the inlet. Specific heat transfer capacities of each system throughout the study and through various tests are listed in Appendix A.

Observations and Results

Much of this study took place throughout the winter; so much of the focus was on how the systems performed in that colder weather where there was not much heat or energy from the sun and to help charge the battery. Both greenhouses were specifically analyzed under special cases; the coldest week, a cloudy week, and a sunny week. Observations were also made from the data of the air sensors at different heights, the thermostat set points, humidity, and insulation.

Coldest Week

The coldest week occurred during Week 14, January 25, 2019, to January 31, 2019, with an average outside air temperature of 20.5°F. Throughout the week the Gray House held its temperature even though the system ran almost constantly drawing energy out of the battery to keep the greenhouse around the thermostat set point of 37°F. In comparison, the thermal energy stored in the climate battery of the Blue House was completely depleted, and the ground temperature dropped several degrees below the exterior ground temperature. Several times the climate battery charged during the day but depleted overnight in an attempt to keep the greenhouse above the set point of 37°F. The results from both houses are shown in Figure 7. This situation shows that the climate battery is able to draw enough thermal energy out of the soil to cool it below the exterior soil temperature. It also showed that the climate battery in the Gray House is more efficient than the Blue House in its ability to store and access energy.



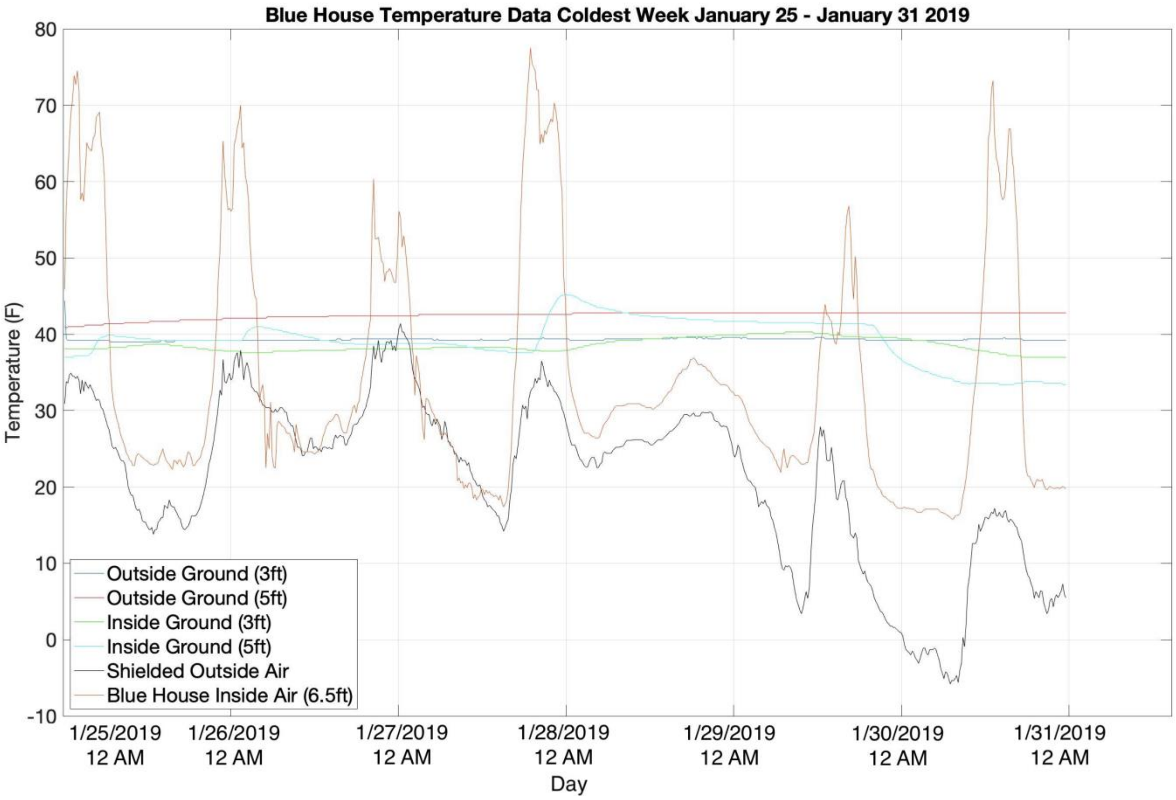


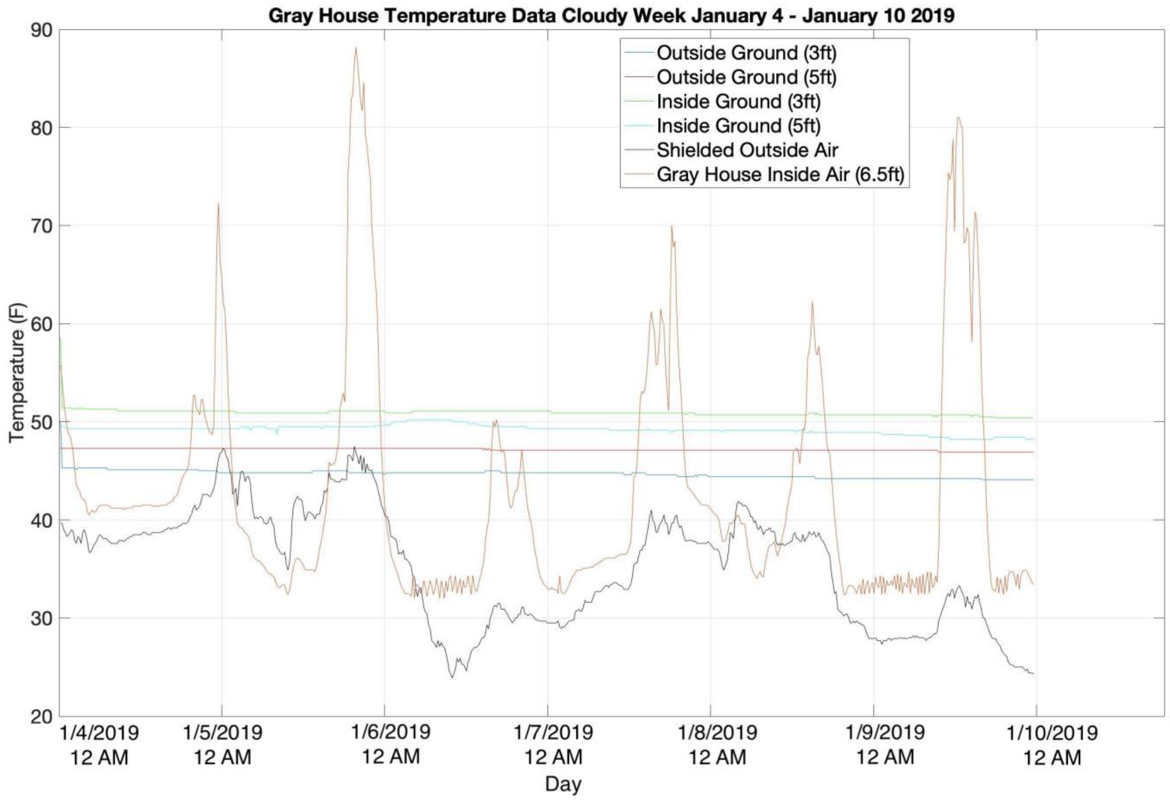
Figure 7: Gray and Blue House data from the coldest week

Cloudy Week

Week 11, January 4, 2019, to January 10, 2019, was cloudy almost every day. This showed if the climate batteries could keep the greenhouses warm with little thermal energy being added by the sun. Graphed in Figure 8, the ground temperature data showed that even without much energy added by the sun the climate battery in the Gray House was able to hold its temperature and keep the greenhouse above 37°F all week. The ground temperature in the Blue House was much less steady and was almost entirely unable to remain above the outside ground temperature. The ground around the lower system was subject to relatively large temperature swings of 5°F, while the upper system was slightly more stable, only changing about 1°F. This shows that the climate battery in the Gray House is storing much more thermal energy than the climate battery in the Blue House. Another factor is the differing amounts of insulation on the canopies of both greenhouses. Much of the energy from the system in the Blue House could be lost to the outside because of its lack of a second layer, and air insulation gap.

Sunny Week

During Week 15, February 1, 2019, to February 7, 2019, it was sunny for the entire week. This gave the batteries the best chance to recharge during the day as the sun warmed the greenhouses. Conveniently this occurred just after the coldest week where toward the end of the week the ground temperatures of both batteries had dropped to be around the same as the outside ground temperatures. Temperatures in the Gray House steadily increased throughout the week as the depleted climate battery recharged. An overall increase in outside temperatures also meant that the greenhouse was not relying on the climate battery as much at night, so the system had time to keep recharging. Similarly, the Blue House charged steadily throughout the week, and the ground temperature data showed a quicker charge time than in the Gray House. This is partially due to the higher temperature difference between the air and the ground, but it also indicates that the Blue House is more efficient at transferring thermal energy from the air to the ground during the cooling cycle. The results are shown in Figure 9.



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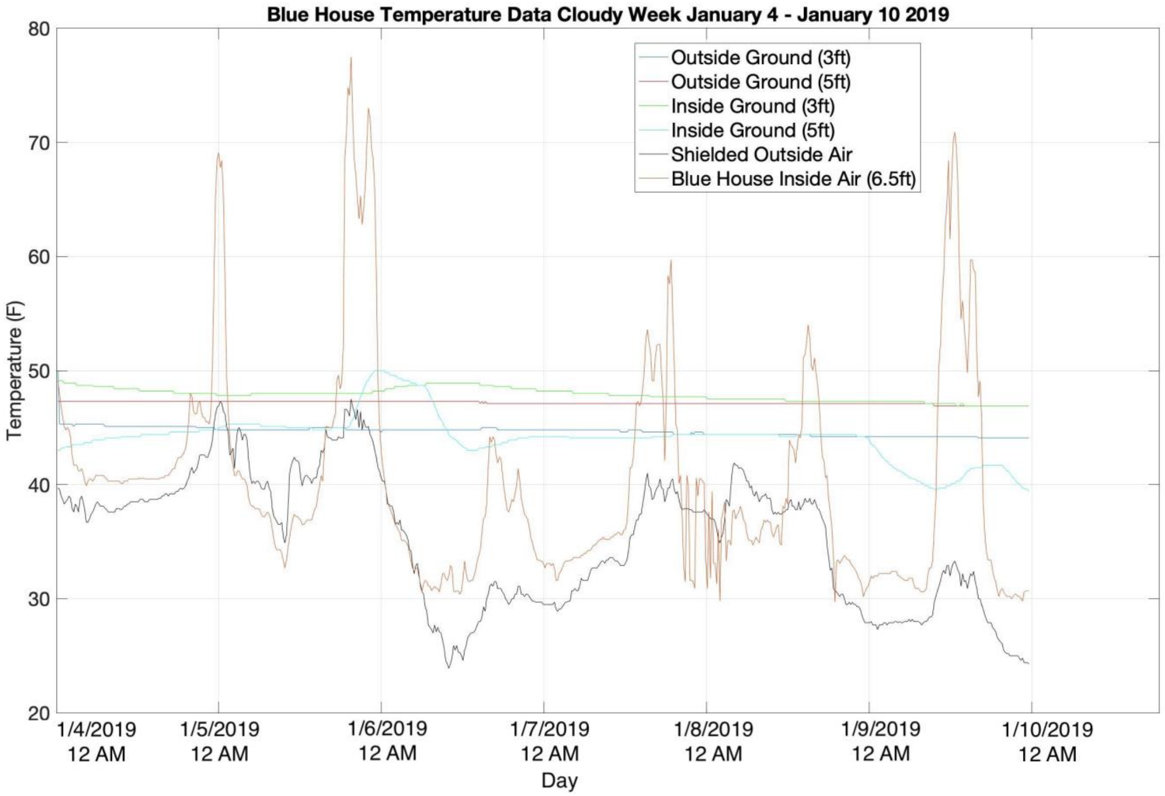
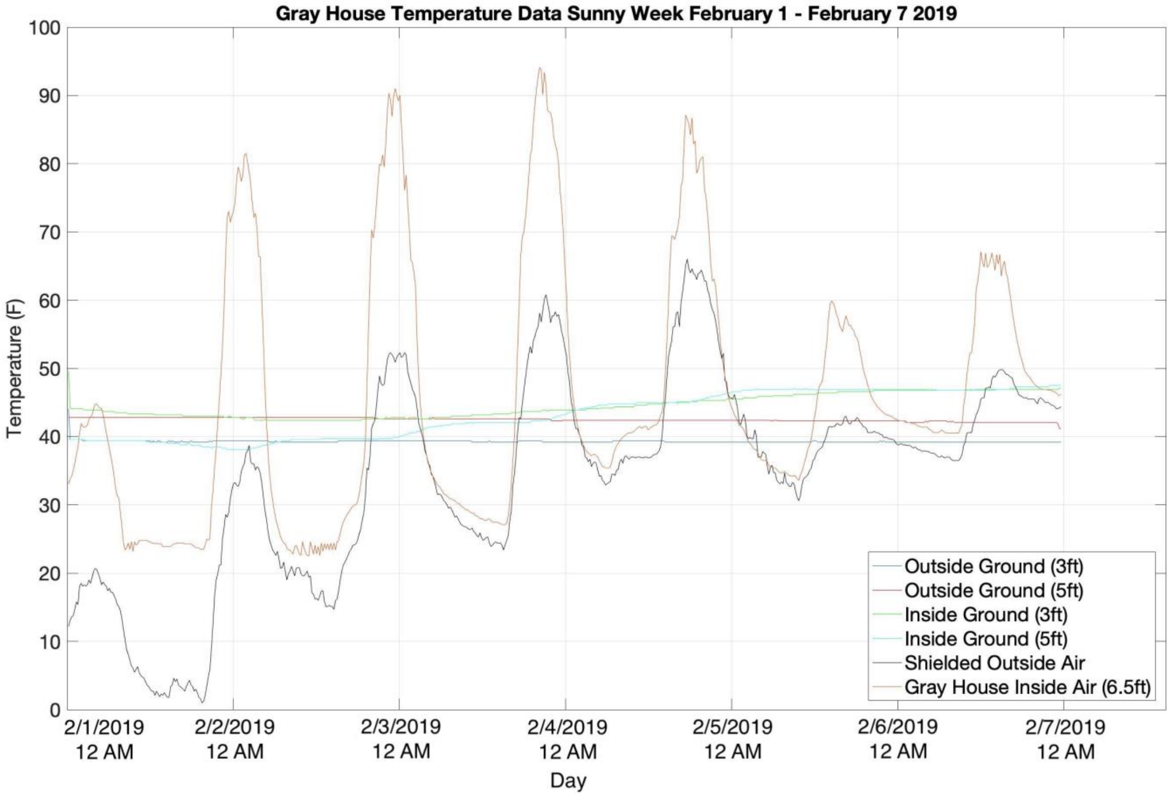


Figure 8: Gray and Blue House data from a cloudy week



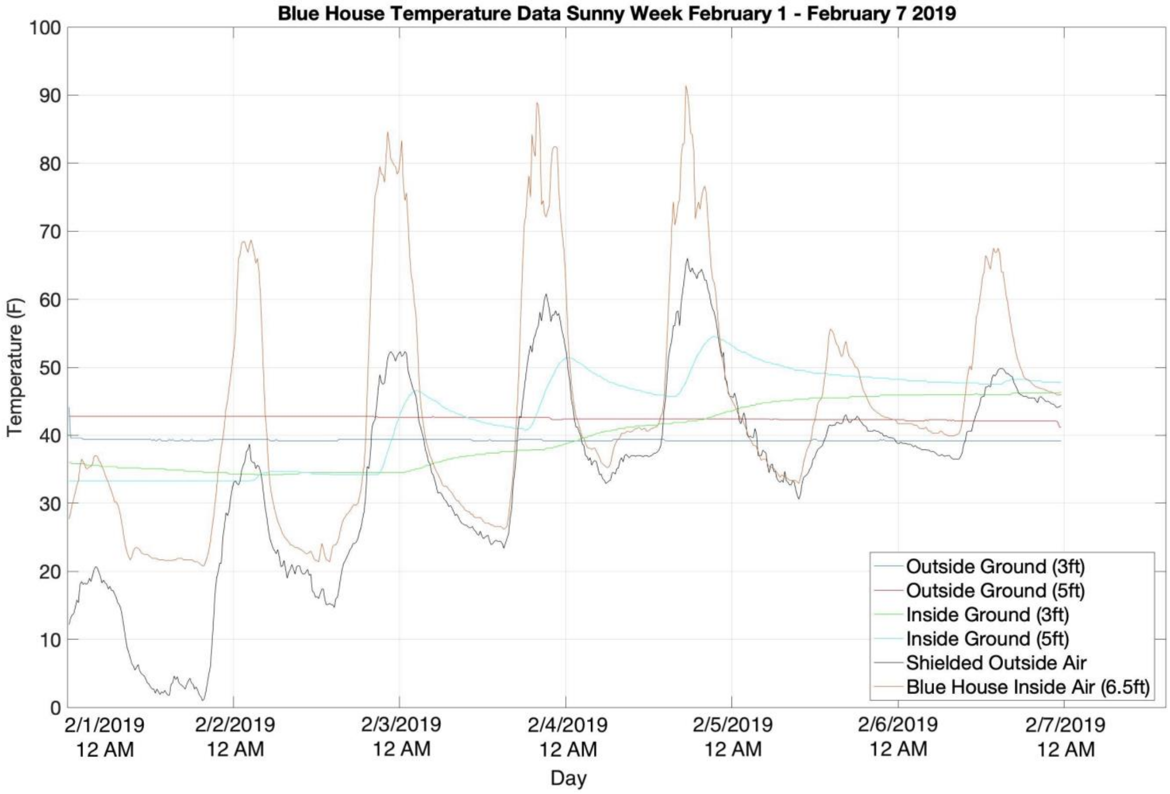


Figure 9: Gray and Blue House data for a sunny week

Air Sensor Elevations

As expected, heat rises, and the air sensor at 1’ recorded lower temperatures than the sensors at 6.5’, which recorded lower temperatures than the sensor at 15’. The graph in Figure 10 shows an average increase of 5°F from low to high sensors. That number is significantly higher during the day, but when coupled with the other temperature data that shows faster charging at larger temperature differences, the batteries could be improved with intakes closer to the top of the greenhouse. Maintenance on the fans and the system is minimal, but the higher they are located, the more difficult it is to access them.

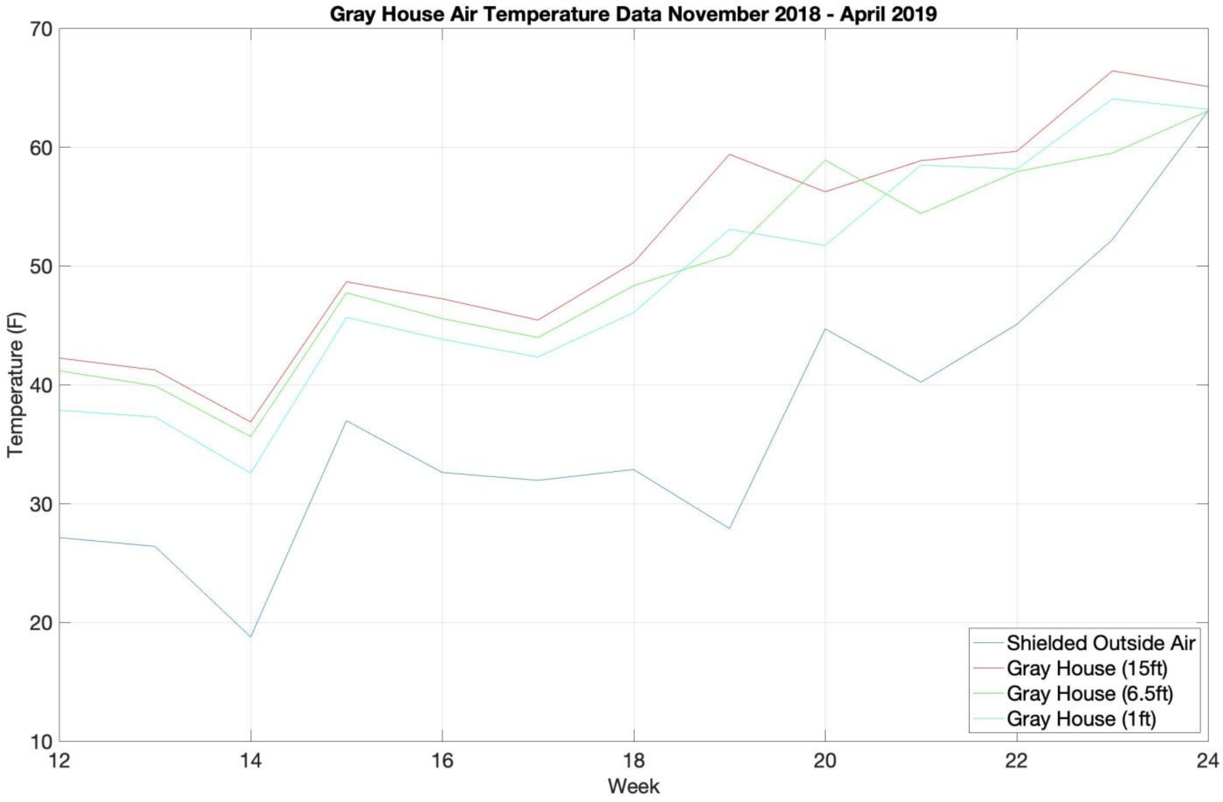


Figure 10: Gray House data from air sensors at different elevations

Set Points

Again, the system charges quicker at larger temperature differences, so the set points should be changed daily to reflect the maximum expected temperature that day to optimize the system performance. Instead of changing them by hand, a programmable controller could possibility be implemented that would set them in relation to the weather forecast, but that was outside the scope of this project.

Effects of Humidity

Research into earth-air heat exchanger systems and methods for improving heat transfer and system effectiveness showed that percent humidity was one thing that was repeatedly referenced. Water has a far better thermal conductivity than air (dry), which is poor enough at heat transfer that it is used as an insulator. The higher the humidity, the more water content in the air, the better the thermal conductivity of the air. That means that the air can transfer heat to and from the ground better. Higher humidity also increases the enthalpy of the air, meaning a pound of air has more BTUs of energy to be transferred. In the winter, however, when temperatures are low, humidity has a minimal effect on air enthalpy, meaning that even with "high" humidity in the winter, the amount of heat transferred will not change greatly over a lower percent humidity.

Insulation

Based on observations of temperature data between both greenhouses, it seems that the Gray House retains its temperature for longer than the Blue House and is noticeably warmer. This temperature difference is partially caused by the different capacities of the two climate battery systems, but also due to their construction and the greenhouses themselves. The double layer of plastic covering the Gray House provides significantly more insulation than the single layer of the Blue House, which means the system in the Blue House needs more output to maintain the same temperature. The reason for this is the coefficient of thermal conduction difference That translates to a 35% decrease in heat loss from the greenhouse simply by adding a second polyethylene layer and inflating the space between them.

Ground insulation is not necessary based on data collected from sensors located just inside and just outside the climate battery footprint. Placing the climate battery completely inside the greenhouse and adding a 4' to 6' buffer zone of soil between the outside wall of the climate battery and the wall of the greenhouse sufficiently insulates the climate battery from heat loss to the outside ground. With this barrier, there seems to be so little heat loss to the outside ground that any attempt to insulate the climate battery system more would likely not be cost effective.

Air Flow

Air is a gas, but in engineering, it is also a fluid, so how it moves is a question of fluid mechanics. At low speeds, air moves in what is known as a laminar flow, it is smooth and uniform. At high speeds, the flow is turbulent, which means it is rough and chaotic, there are swirls and the molecules are colliding with the wall of the pipe. The speed may be higher, but the indirect path and increased molecular collisions mean that the air is spending more time and transferring more energy. Therefore, turbulent flow is the ideal flow type in the tubes. Flow is considered turbulent if the Reynolds Number is greater than 4000, which is calculated from the density, dynamic viscosity, and velocity of the fluid and diameter of the tube. For a 4" tube, the Airspeed needs to be around 125 feet per minute (fpm) or 0.635 meters per second (m/s).

Gray House

It was expected that the Airflow through each tube would be different, that the majority of the air would blow over the connection between the manifold and the first tubes, and be forced down the ones at the end of the manifold. The 18" manifold and 24" risers of the Gray House are large enough that a person can fit inside them, so airflow readings from each tube were taken with an anemometer, with results shown in Appendix B. The data behaved as expected, and ranged from around 200 to 1000 fpm, all turbulent.

Since the Airflow was uneven, the heat transfer most likely was too. Baffles made of short, halved pieces of the same 4" tubing were inserted into the first 20 to 25 tubes of one system in an effort to divert more air through them, shown in Figure 11. The original, center system was left unmodified. Data collection after installation, also in Appendix B, showed a larger reduction in the high flows than the increase in the low flows, but the readings were more uniform across all tubes. Baffling was also installed in the third system, and a booster fan was placed in the exhaust riser to test its effectiveness, again with the central system as a control. Ground sensors were relabeled and placed in the modified systems to measure any temperature differences in comparison to the control. As shown in Figure 12. the baffles themselves actually decreased the system performance, but the addition of baffles and an exhaust fan increased the output by 1°F or 2°F.

Figure 11: Installed baffles in Gray House system

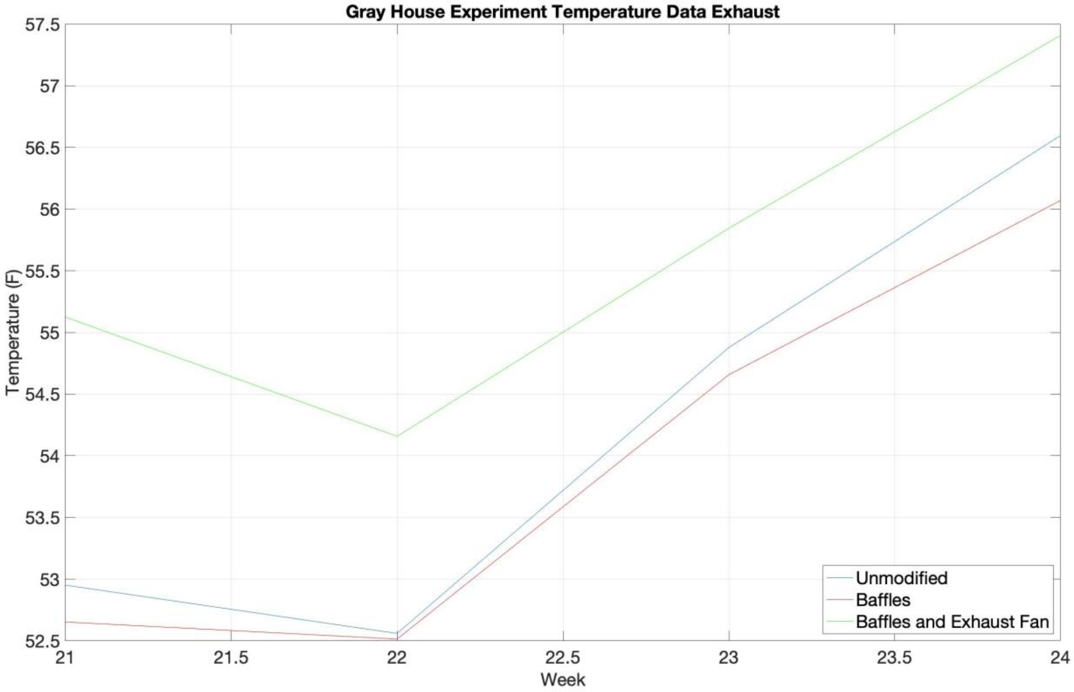


Figure 12: Gray House tests exhaust temperatures

Blue House

There was no way to access the tubes in the 6” risers and manifolds of the Blue House, so simulation was the answer. COMSOL models showed the Airflow reaching speeds of about 0.08

to 0.09 m/s across the tubes, which is very laminar in comparison to the 0.635 for turbulent flow. The simulation results are shown below in Figure 13. The 425 CFM fans were the largest available for a 6” pipe size but are the reason for the low airspeed. The simulation was repeated for a 12” fan with a 2050 CFM output, still in the 6” pipes, which gave values of 0.41 to 0.50 m/s, which are better, but not yet turbulent. Utilizing 12” pipes with the 2050 CFM fan, in Figure 14, the speeds jumped to between 2.05 and 2.13 m/s, which is now very turbulent. Adding wye fittings to help direct the air into the tubes was also simulated. Figures 13 and 14 show the airspeed as fastest in the center of the tube and slowing down around the edges. Wye fittings did not significantly change the speed from the straight tubes, but did make it uniform across the tube diameter, which would increase the heat transfer from the air to the tubes, and ultimately the air to the earth.

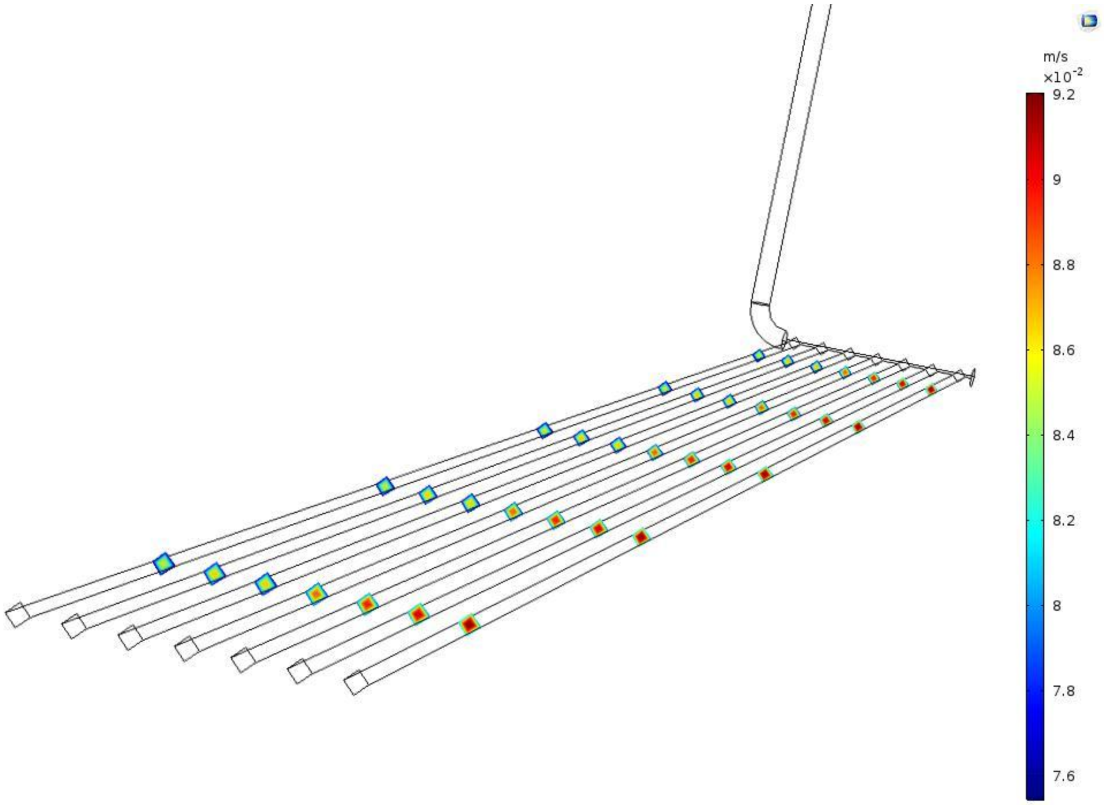


Figure 13: COMSOL data for Blue House system with 6” pipes and 425 CFM

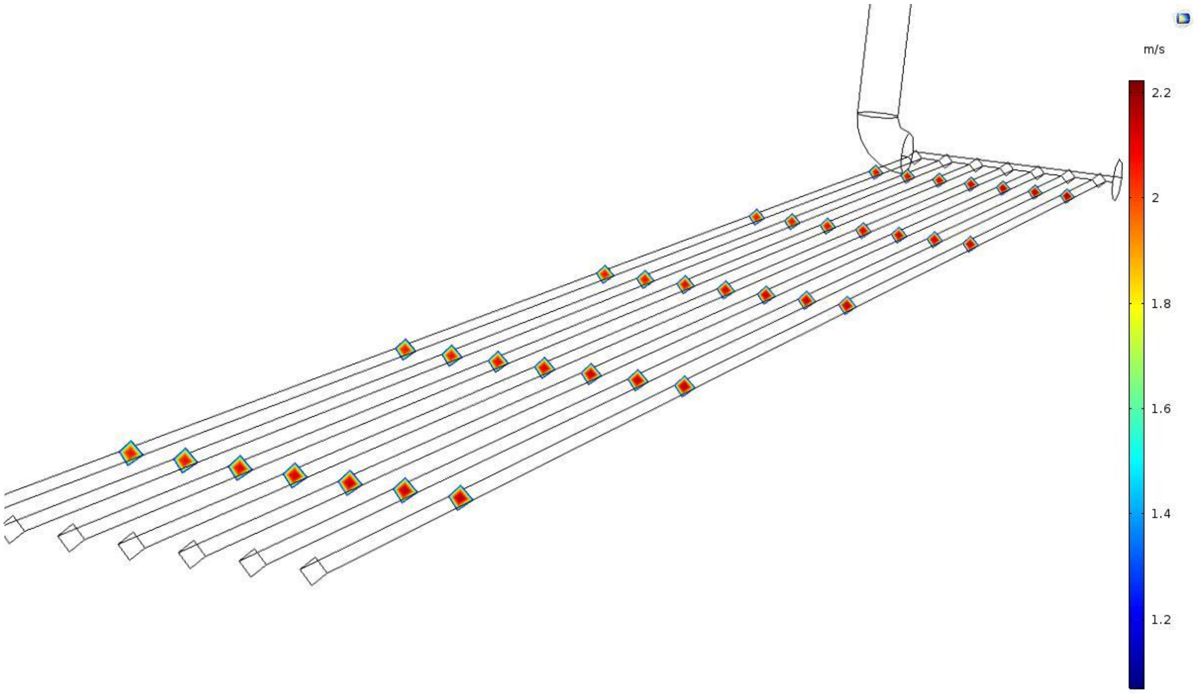


Figure 14: COMSOL data for Blue House system with 12" pipes and 2050 CFM

One test that was able to be performed on the Blue House system was the addition of booster fans to help increase airflow. They were initially added just to the 6’ systems. There was an increase in heat transfer between the two layers, but it cannot be attributed solely to the boosters due to the different depths as another variable.

Mini Greenhouse

A small 6’ x 15’ greenhouse was used inside the Blue House with additional heaters to start a variety of plants during the winter. It was repurposed to test two small scale systems that would give a direct comparison. From the Blue House, the use of stone backfill around the tubes allowed air to move through the stone. During initial construction, turning on one fan would cause air to flow out of all the risers, traveling through the stone. When all of the fans are on in operation, the air pocket is filled up and the air travels through the pipes, but since stone is a better insulator than soil, and would have more surface area for heat transfer than tubes, what if there were no tubes installed at all? One test system would consist of a 6” inlet and an exhaust riser at either end of a stone bed, and the other would be a smaller manifold and tube system identical to the Blue House but backfilled with soil. Each system was placed in a 3’ x 12’ footprint around 4’ deep. There were three tubes connecting the manifolds in one, and 2’ of R4 stone in the other, both powered by the 425 CFM fans. The systems ran for two weeks before the greenhouse cover began to fail from the wind, ending the test. Both systems ran largely in cooling mode, except for cold night or two. The stone system performed well, removing more heat from the air in cooling mode and being able to give more back in heating mode, though at a lower airspeed than the tubed system. Installation and material costs would also be lower for a stone system, as there are minimal piping needs and less excavation to install individual trenches. There are more losses in the stone, so the fans would need to be larger, but it is a promising alternative.

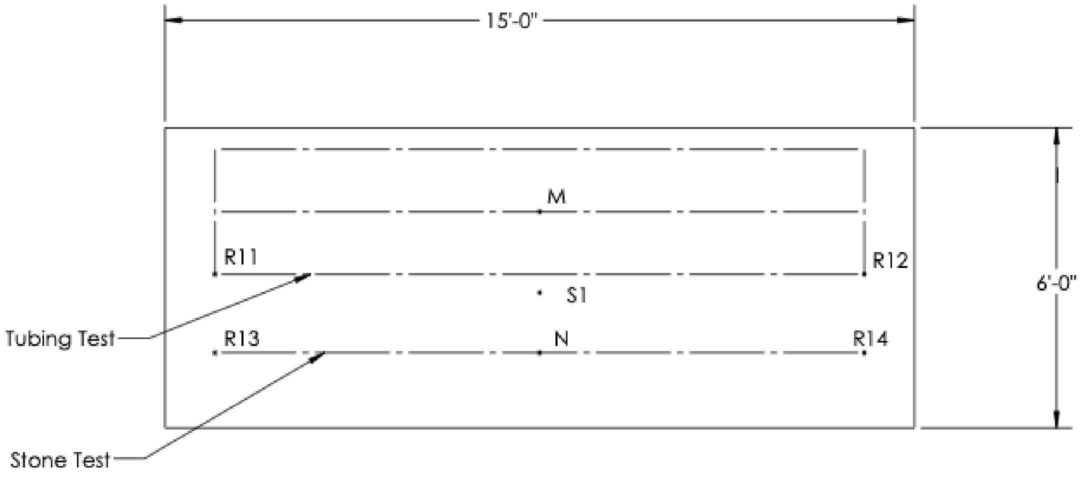


Figure 15: Mini greenhouse schematic

Chapter 4: Recommendations and Conclusions

Climate Battery Design Recommendations

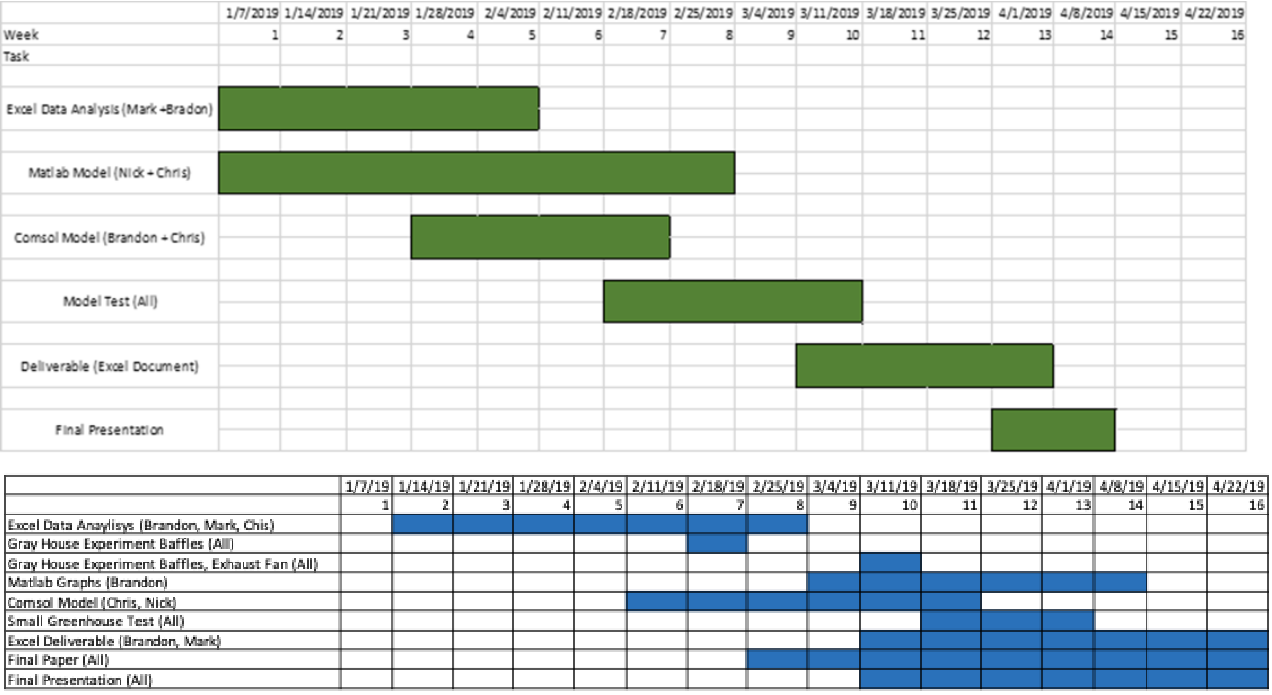
To conclude the study some recommendations were requested for improvement of future climate batteries. After extensively studying the operation of both climate batteries it is recommended that future climate batteries use a system similar to the gray house with some adjustments to improve function. Placing tubes directly in the soil instead of in stone is much more efficient when using the climate battery to heat because the tubing system can access the heat. Stone is a very good insulator, and therefore is not recommended around the tubes. It is best to space tubes 12 inches center to center to gain maximum heat transfer into the soil during charging cycles. Placing tubes too close together causes the soil to become saturated with heat quickly which will cause it to no longer store any more heat. Adding baffles, or staggering tubes in the manifolds to promote even airflow throughout each tube is recommended to increase the even spread of heat throughout the climate battery. Primary fans in the risers should have a high CFM rating. In the gray house climate battery at Threefold Farm, the primary fans were rated to 5,000 CFM. These fans worked very well for pushing air through the climate battery system. Adding booster fans to the exhaust risers of each climate battery system will also increase heat transfer by moving more air through the system and increasing the turbulence of the air in the system to promote a higher rate of heat transfer. Four to six feet of soil should be left between the outside of the climate battery and the outside of the greenhouse to prevent unnecessary heat losses from the climate battery to the ground outside the greenhouse. Maintaining a high humidity rate in the greenhouse allows air to hold thermal energy longer and transfer its thermal energy better. It is recommended to keep relative humidity inside climate battery greenhouses as high as possible to increase the rate of heat transfer. Lastly, to increase the temperature of air drawn into a climate battery system it is recommended to elevate inlet risers to a height that allows the system to draw air from a warm part of the greenhouse. Since heat rises the higher the risers are located the better.

Future Capstone Studies

This study is planned to be continued with next year's group of capstone students. There were many things that there is not enough data currently to draw definite conclusions about. Further investigation into the system controllers is one of the potential areas of focus for future groups. The potential to add a programmable controller to run the system and allow for more fluid set points has the potential to improve the system effectiveness greatly. Aside from system controllers, the actual design of the system is something else that needs further research. The small-scale stone bed test yielded potentially promising results, however, due to a lack of time, the tests of it could not be completed and need to be revisited. The other design aspect that needs further study is having more than one “layer” of tubing. Results were inconclusive as to how effective or ineffective having more than one layer of tubing is in improving the system’s output. Another area of focus would be to determine the ideal length of tubing for the system to maximize heat transfer. Our study concluded that for the fan speed there was no max tubing length shorter than the greenhouse structures in use at Threefold Farm, however knowing max tubing length could be useful for installation in a gutter connect greenhouse. Another point of the study is painting the riser tubes black to increase the temperature of the tubes. This was unable to be studied due to a lack of time but could be a low-cost way to increase the temperature of the air inside the risers.

Chapter 5: Capstone Documents

Work Breakdown Structure



	1/7/2019	1/14/2019	1/21/2019	1/28/2019	2/4/2019	2/11/2019	2/18/2019	2/25/2019	3/4/2019	3/11/2019	3/18/2019	3/25/2019	4/1/2019	4/8/2019	4/15/2019	4/22/2019
Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Task																
Excel Data Analysis (Mark +Bradon)	🟩	🟩	🟩	🟩	🟩											
Matlab Model (Nick + Chris)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩								
Comsol Model (Brandon + Chris)				🟩	🟩	🟩	🟩									
Model Test (All)							🟩	🟩	🟩	🟩						
Deliverable (Excel Document)										🟩	🟩	🟩	🟩			
Final Presentation													🟩	🟩		

	1/7/19	1/14/19	1/21/19	1/28/19	2/4/19	2/11/19	2/18/19	2/25/19	3/4/19	3/11/19	3/18/19	3/25/19	4/1/19	4/8/19	4/15/19	4/22/19
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Excel Data Anaylisys (Brandon, Mark, Chis)		🟦	🟦	🟦	🟦	🟦	🟦	🟦								
Gray House Experiment Baffles (All)							🟦									
Gray House Experiment Baffles, Exhaust Fan (All)										🟦						
Matlab Graphs (Brandon)									🟦	🟦	🟦	🟦	🟦	🟦		
Comsol Model (Chris, Nick)						🟦	🟦	🟦	🟦	🟦	🟦					
Small Greenhouse Test (All)											🟦	🟦	🟦			
Excel Deliverable (Brandon, Mark)										🟦	🟦	🟦	🟦	🟦	🟦	🟦
Final Paper (All)								🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Final Presentation (All)										🟦	🟦	🟦	🟦	🟦	🟦	🟦

Figure 16: Responsibility, breakdown, and schedule. Green is proposed, blue is actual

Parts List and Budget

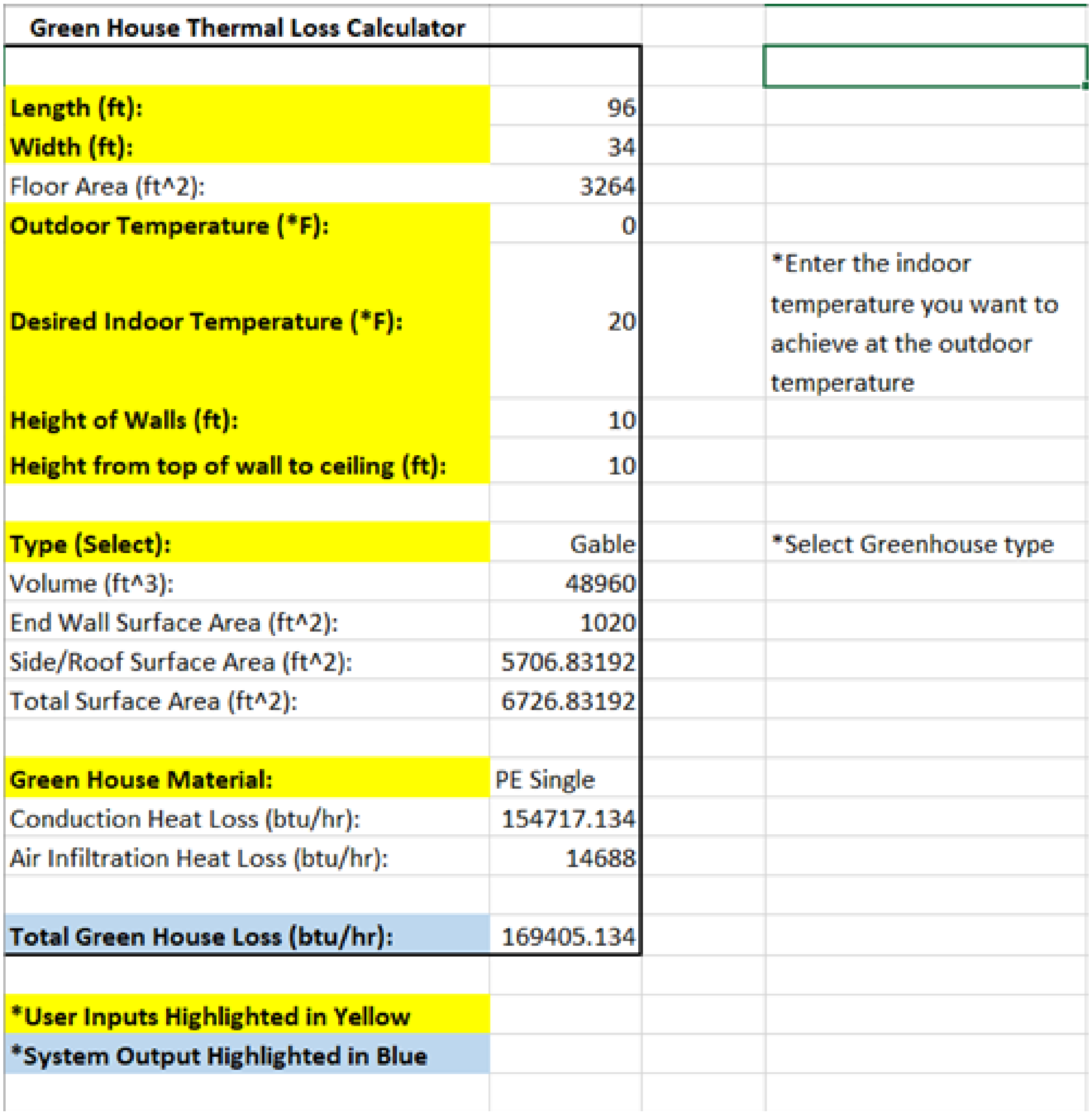
This project started with a budget of $1,500. After purchasing sensors and materials for installation, the total cost was under $1,200. The breakdown is shown in Table 2.

Product	Quantity	Price ($)
Elitech RC-4	39	21.50
Elitech RC-4HC	5	36.99
Elitech RC-5+	1	24.99
Heatshrink	1	5.99
1/2" x 10' Conduit	20	2.16
1/2" Conduit 90^0 Elbow	8	0.64
1/2" PVC Cap	12	0.47
Silicone Caulk	1	2.98
Zip Ties	1	7.98
Total		1119.4

Table 2: Bill of Materials

Deliverable

One of the deliverables created using the research that has been done and the data that has been collected is an excel calculator for green house climate batteries. The calculator has two parts, a greenhouse heat loss calculator (figure 13) and a climate battery recommendation calculator based on the loss calculator. To use the calculator a user enters the length, width, height, and type of the greenhouse they have or plan to use. The user then enters the outdoor temperature and the desired indoor temperature they want to reach. Finally, the user selects the material the green house is made with (glass, polyethylene, etc.). The calculator then returns what the total greenhouse loss is in BTU/hr by calculating the conduction heat loss and the air infiltration heat loss. The second part of the calculator then takes the total required BTU/hr and the length and width of the greenhouse and returns the number of tubes and their length needed to achieve that BTU/hr.



Green House Thermal Loss Calculator		
Length (ft):	96	
Width (ft):	34	
Floor Area (ft^2):	3264	
Outdoor Temperature (*F):	0	
Desired Indoor Temperature (*F):	20	*Enter the indoor temperature you want to achieve at the outdoor temperature
Height of Walls (ft):	10	
Height from top of wall to ceiling (ft):	10	
Type (Select):	Gable	*Select Greenhouse type
Volume (ft^3):	48960	
End Wall Surface Area (ft^2):	1020	
Side/Roof Surface Area (ft^2):	5706.83192	
Total Surface Area (ft^2):	6726.83192	
Green House Material:	PE Single	
Conduction Heat Loss (btu/hr):	154717.134	
Air Infiltration Heat Loss (btu/hr):	14688	
Total Green House Loss (btu/hr):	169405.134	
***User Inputs Highlighted in Yellow**		
***System Output Highlighted in Blue**		

Figure 17: Sample screen from deliverable

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Appendix A: System Performances and Comparisons

This section contains all of the system capacities in BTU/hour in normal operation and throughout any tests and modifications.

Gray House Tests Heat Transfer Rates

Test Set	Heat Transfer Rate Per System Heating (BTU/hr)	Heat Transfer Rate Per System Cooling (BTU/hr)
Unmodified System (R1,R2)	30,462.08	49,293.60
Baffles in 23 Tubes (R7,R8)	34,185.97	47,723.98
Baffles in 23 Tubes, Booster Fan (R9,R10)	38,479.82	56,213.28

Blue House Heat Tests Transfer Rates

Test Set	Heat Transfer Rate Per System Heating (BTU/hr)	Heat Transfer Rate Per System Cooling (BTU/hr)
Unmodified System (R3,R4)	17,157.67	75,453.72
Modified System (R5,R6)	23,231.90	89,969.30

Entire Greenhouse Heat Transfer Rates

Greenhouse	Heat Transfer Rate Heating (BTU/hr)	Heat Transfer Rate Cooling (BTU/hr)	Sample Calculation
Gray	103,127.87	153,230.86	HTR = R1R2 + R7R8 + R9R10
Blue	242,337.42	992,556.12	HTR = (R3R4*6) + (R5R6*6)

Adjusted Greenhouse Heat Transfer Rates

The Gray house operates at 0.80 efficiency and the Blue House operates at 0.56 efficiency.

Greenhouse	Heat Transfer Rate Heating (BTU/hr)	Heat Transfer Rate Cooling (BTU/hr)	Sample Calculation
Gray	82,502.30	122,584.69	AHTR = HTR * 0.8
Blue	135,708.96	555,831.43	AHTR = HTR * 0.56

Climate Battery Coefficient of Performance

Greenhouse	Total Fan Power Draw (kW)	Coefficient of Performance	Sample Calculation
Gray	1.2	32.69	COP = HTR / (P * 3412)
Blue	0.924	6.81	COP = HTR / (P * 3412)

Appendix B: Gray House Air Flow Test Results

Tube Number (Front to Back)	Air Speed Without Baffles (ft/min)	Flow Without Baffles (CFM)	Air Speed With Baffles (ft/min)	Flow With Baffles (CFM)	Delta Air Speed (ft/min)	Delta Flow (CFM)
1	N/A	N/A	1043.00	204.79	N/A	N/A
2	N/A	N/A	925.00	181.62	N/A	N/A
3	900	176.71	1122.00	220.30	222.00	43.59
4	960	188.50	1102.00	216.38	142.00	27.88
5	980	192.42	984.00	193.21	4.00	0.79
6	940	184.57	905.00	177.70	-35.00	-6.87
7	905	177.70	885.00	173.77	-20.00	-3.93
8	866	170.04	905.00	177.70	39.00	7.66
9	980	192.42	843.00	165.52	-137.00	-26.90
10	660	129.59	826.00	162.18	166.00	32.59
11	866	170.04	807.00	158.45	-59.00	-11.58
12	708	139.02	393.00	77.17	-315.00	-61.85
13	800	157.08	570.00	111.92	-230.00	-45.16
14	826	162.18	334.00	65.58	-492.00	-96.60
15	860	168.86	236.00	46.34	-624.00	-122.52
16	905	177.70	374.00	73.43	-531.00	-104.26
17	630	123.70	334.00	65.58	-296.00	-58.12
18	760	149.23	413.00	81.09	-347.00	-68.13
19	300	58.90	314.00	61.65	14.00	2.75
20	670	131.55	354.00	69.51	-316.00	-62.05
21	670	131.55	452.00	88.75	-218.00	-42.80
22	650	127.63	236.00	46.34	-414.00	-81.29
23	570	111.92	314.00	61.65	-256.00	-50.27
24	610	119.77	334.00	65.58	-276.00	-54.19

25	610	119.77	314.00	61.65	-296.00	-58.12
26	452	88.75	354.00	69.51	-98.00	-19.24
27	531	104.26	354.00	69.51	-177.00	-34.75
28	650	127.63	452.00	88.75	-198.00	-38.88
29	531	104.26	255.00	50.07	-276.00	-54.19
30	413	81.09	354.00	69.51	-59.00	-11.58
31	511	100.33	393.00	77.17	-118.00	-23.17
32	452	88.75	314.00	61.65	-138.00	-27.10
33	413	81.09	354.00	69.51	-59.00	-11.58
34	511	100.33	314.00	61.65	-197.00	-38.68
35	492	96.60	374.00	73.43	-118.00	-23.17
36	320	62.83	334.00	65.58	14.00	2.75
37	255	50.07	295.00	57.92	40.00	7.85
38	236	46.34	354.00	69.51	118.00	23.17
39	236	46.34	354.00	69.51	118.00	23.17
40	275	54.00	275.00	54.00	0.00	0.00
41	295	57.92	374.00	73.43	79.00	15.51
42	216	42.41	413.00	81.09	197.00	38.68
43	334	65.58	492.00	96.60	158.00	31.02
44	295	57.92	433.00	85.02	138.00	27.10
45	334	65.58	452.00	88.75	118.00	23.17

Appendix C: Thermostat Set Points

Gray House

Date of Change	Level		Thermostat Diff
	High	Low	Heat Diff;Cool Diff
9-Nov	76	39	3;3
20-Nov	76	37	3;3
6-Dec	65	34.5	2;2
12-Dec	65	34.5	2;2
1-Jan	65	34.5	2;2
15-Jan	65	28.5	2;2
23-Jan	65	26.5	2,2
28-Jan	65	24.5	2,2
21-Feb	70	26.5	2;2
4-Mar	70	32.5	2;2
7-Mar	75	34.5	2;2
4-Apr	80	50	2;2

Blue House

Date	**Upper Level**			**Lower Level**		
	High	Low	Heat Diff;Cool Diff	High	Low	Heat Diff;Cool Diff
9-Nov	85	40	3;3	75	40	3;3
20-Nov	75	37	3;3	75	37	3;3
6-Dec	65	32.5	3;3	65	32.5	3;3
12-Dec	60	32.5	3;3	60	32.5	3;3
1-Jan	65	32.5	3;3	65	32.5	3;3
15-Jan	65	24	3;3	65	24	3;3
23-Jan	65	24	3;3	65	25	3;3
28-Jan	65	23	3;3	65	24	3;3
21-Feb	70	23	3;3	70	24	3;3
4-Mar	70	23	3;3	70	24	3;3
7-Mar	75	23	3;3	75	24	3;3
4-Apr	80	40.5	3;3	80	40	3;3