# HEATING SEASON GAHT GREENHOUSE ENERGY STORAGE

A Thesis
by
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## Abstract

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This thesis provides a baseline characterization of an Earth-to-Air Heat Exchanger in the context of a high efficiency greenhouse structure during the month of February in Ashe County, North Carolina. The Ceres High Efficiency Greenhouse Solutions trademarked Ground-to-Air Heat Transfer (GAHT) system functions as a thermal energy storage technology. This study aims to characterize the function and efficiency of the GAHT system in the Appalachian Mountains during the month of February in its heating season. In this paper four research questions are answered related to latent heat transfer, total energy storage, and coefficient of performance. For this data set, the GAHT is capable of storing a daily average of 128,588 BTU (37.7 $kWh_{TH}$). It held an average Coefficient of Performance of 2.38 when continuously running. The paper provides a review of relevant literature, gives greenhouse and thermal energy storage background, and describes methods and analysis to find and evaluate performance metrics for the results numbers.

*Keywords*: Greenhouse, Thermal Energy Storage, Earth-to-Air Heat Exchanger, Ground-to-Air Heat Transfer

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**Contents**

# Introduction

## Importance of Greenhouses

This work aims to study thermal energy storage technology in a greenhouse context. First the importance of greenhouse technology will be outlined. Then the discussion will focus toward the specific study of high efficiency greenhouses, and subsequently narrow in on earth-to-air heat exchange systems and their experimental study.

A greenhouse can be broadly defined as an enclosed or semi-enclosed space made with transparent materials for the production or protection of plants. Greenhouses are a critical agricultural technology. For instance, Hanan (1997) identified how greenhouses are vital to global food production. Indoor agriculture allows for geographically limited areas to increase the consistency and productivity of crops. Plants can stay warmer year-round, and thereby extend the growing season. Greenhouse use increased worldwide by 12% between 2015-2020, and is expected to grow further in the coming five years (Graves, 2021).

The benefits of greenhouses are primary due to a few factors. Greenhouses extend growing seasons by maintaining growing conditions even while ambient conditions are not suitable. They protect plants from extreme weather events that can destroy entire crops in the span of days, hours, and even minutes. Lastly, greenhouses give farmers increased control over growing conditions to optimize food production and increase consistency in the crop (Stranghellini, 2014).

The Intergovernmental Panel on Climate Change (IPCC, 2021) mentions in their 2021 Climate Change Report that greenhouses are an important factor in maintaining semi-stable growing conditions for agricultural production. This stability is necessary to shield against extreme or prolonged weather events that may ruin a crop. Those weather events are expected to increase in frequency as a result of climate change. This makes development of greenhouse technology an important focus.

The specific design of a greenhouse can be rudimentary to highly complex and automated. There are a variety of structures that might be associated with greenhouses. From the basic hoop house to the high efficiency greenhouse, there are many styles in which greenhouses can be constructed. For clarity, Tables 1 & 2 provide definitions and functions for each structure and construction method. Heated high performance greenhouses will be the focal point of this study.

**Table 1:** *Greenhouse Types and Features (Schiller & Plinke, 2016)*

| Greenhouse Type | Identifying Features |
|---|---|
| High Tunnel | General name for greenhouses with a curved roof and longer ground-posts for height |
| Hoop-House/Quonset Greenhouse | Curved roof supported by hoops made of PVC or Aluminum, with plastic film stretched across |
| Industrial Greenhouse | Large-scale constructions built with professional standards and including control systems |
| Gothic Arch Greenhouse | Rounded walls coming to meet at a central point, similar to the hoop-house but wider and can work better for snow loads at scale |
| Lean-To Greenhouse | Attached to an existing building on a southern wall, extending the roof and enclosing the area |
| A-Frame Greenhouse | Triangle structure freestanding greenhouse with poorer air circulation, when connected in multiples becomes a Ridge and Furrow Type Greenhouse |

| | |
|---|---|
| Cold Frame Greenhouse | Raised garden bed with a glazed sloping lid |
| Hotbed Greenhouse | Cold frame with heating capacity installed |
| Greenhouse with Films | Plastic covering used often with hoop-house type constructions, providing more flexible coverage with a variety of options |
| Greenhouse with Rigid Sheets | Normally with polycarbonate, fiberglass, or acrylic sheets, these constructions are generally sturdier and meant for square structures |
| Passive Solar Greenhouse | Greenhouse designed to not need heating inputs beyond what is provided by the sun and thermal mass within the structure |
| High Performance Greenhouse | Complex enclosed greenhouse system designed with automated controls and engineered for environmental parameters of cultivation |

**Table 2:** *Greenhouse Construction Options*

| Greenhouse Construction Type | Summary |
|---|---|
| Conventional Wood or Stick Frame | Small to mid-size standard greenhouse construction for residential use |
| Pole Barn | Mid- to large sized greenhouse construction requiring posts or piers for greater structural stability |
| Aluminum Frames & Kit Greenhouses | Small to large sized greenhouse construction with metal framing for assembled kits allowing commercial construction |
| Galvanized Steel Frame | Mid to large sized greenhouse construction for areas with wind or snow loads requiring more durable framing |
| Structurally Insulated Panels (SIPS) | Small to large sized greenhouse construction using prefabricated wall sections with higher insulation |
| Natural Building Methods | Small size greenhouse construction using natural materials such as hay and cob |

**The Modern Heated Greenhouse**

There are a wide range of applications of modern heated greenhouses. Industrialized operations may have upwards of 70 acres all under a greenhouse (USDA, 2007). For small to mid-sized farmers, it is more common to have 1-6 greenhouses. Home owners may have a small 4 m² structure for personal use. This study focuses on greenhouses used for the small to mid-sized farmer.

Within the realm of greenhouses for the small farm, again there are options. A farmer may select a more conventional structure made out of a metal frame and glazing or film that allows light transmission. Table 3 identifies several classifications of greenhouse glazing that you might find on a farm. This study will focus on high performance greenhouses.

**Table 3:***Greenhouse Glazing Materials (Goldammer 2019)*

| Glazing Material | Types | Characteristics |
|---|---|---|
| Plastic Films | ● Polyethylene Film<br>● Polyvinyl Chloride Film<br>● Polyester Film | More cost effective, and have good initial light transmittance and ease of installation |
| Rigid Plastics | ● Polycarbonate<br>● Fiberglass-Reinforced Plastic Rigid Panel<br>● Acrylic (Polymethyl Methacrylate) | Easier to install than glass, and allow for similar light transmittance until UV yellowing occurs |
| Plastic Additives | ● IR Blocking Materials<br>● Anti-Condensation Inhibitors<br>● UV-Blocking Materials<br>● Light Diffusion Materials<br>● Anti-Dust Inhibitors | Some rigid plastics and polyethylene film formulated for better preferential control of light and heat energy both entering and radiating out of a greenhouse |
| Glass | ● Tempered<br>● Laminated<br>● Frosted | Oldest most traditional glazing, most expensive material with some higher operating costs |

**Resource Streams Outside of Cultivation**

When looking at the inputs needed for a greenhouse to maintain temperature and moisture levels, there are several basic energy and resource streams to consider. These inputs can be grouped into the following categories:

- Electricity
- Fossil Fuel
- Solar
- Water

Electricity may be needed to run lights, fans, heating, cooling, pumps, and/or automation systems. This can consume around 7.6 Watts per square meter per degree Celsius of temperature change needed depending on the size of the greenhouse (Haase & Rath, 2014).

If the greenhouse is running year-round, particularly in regions with cold winters, then fossil fuel for heating is a major greenhouse input. Most producers will run propane heaters to maintain indoor temperatures. Based on the U.S. Energy Information Administrations' 2021-2022 Winter Propane Market Update, running one 100 BTU/hour heater for a night costs approximately $10. This number can vary depending on the heater, the space needing heating, both indoor and outdoor temperatures, as well as the needs of the plants being grown (U.S. EIA, 2022).

The main greenhouse heat source year-round comes from the sun. The indoor environmental impacts of solar gain are linked to ambient conditions, greenhouse construction, and thermal storage. For instance, a high-performance greenhouse may remain above freezing on days approaching 0°F (Schiller & Plinke 2016). A high tunnel in the same circumstance would likely not fare so well.

Water is another essential input when running a greenhouse. Plants need water in order to survive, and because of the nature of an enclosed greenhouse structure, irrigation is a necessity.

Since greenhouses are by nature enclosed structures, rain does not water the plants. Often drip irrigation systems are installed or hydroponic systems in addition to hoses for watering plants. Depending upon location and the availability of water resources, irrigation inputs can range in terms of financial considerations of a greenhouse.

**Energy Considerations**

For the modern heated greenhouse, energy consumption begins to play a factor. There may be several energy inputs that are necessary. The following is a typical list of energy loads in a greenhouse:

- Heating
- Mechanical Ventilation
- Lighting
- Pumps
- Monitoring and Controls

Lighting energy can be a major cost in greenhouse operations in some circumstances. For instance, a study by Aarhus University (Jørgensen, 2011) has found a 50-80% reduction in greenhouse lighting costs in Denmark by switching to LED lighting and implementing more effective lighting controls for fall and spring months.

More typically, heating is a primary factor. Most producers will run propane heaters to maintain indoor temperatures during the coldest winter days and nights, but it can be risky to only rely on a single energy source. Heat can be lost through leakage of the greenhouse envelope, conduction through the ground or building materials, and radiation through the glazing. Heat from the sun can be stored in thermal mass such as water barrels or soil within the greenhouse.

**High Performance Greenhouses**

As technology progresses, greenhouses are an area for improving environmental control and energy efficiency for better results. High performance greenhouses have the goal of reducing input needs and maintaining environmental control. This combines greater efficiency with backup heat supply to ensure the survival of plants in the greenhouse. Other characteristics of high performance greenhouses include increased stability, longevity, and climate control.

The performance of a greenhouse centers on its ability to maintain environmental control for consistent crops, and efficiency measures allow this to be done with less energy inputs. Performance improvements can include:

- Better envelope
- Lighting technology
- HVAC systems
- Thermal storage

When comparing the building envelope of a high-performance greenhouse with its insulated metal panels and glazing which are incredibly tight, with highly reduced air infiltration and leakage, alongside a traditional hoop house consisting of polyethylene plastic, there are efficiency advantages as well as stability to consider.

For the modern high-performance greenhouse, some key goals are environmental control and energy efficiency. Environmental control is related to providing the right thermal, lighting, and airflow conditions for plants to grow best. To maintain environmental control, in a high-performance greenhouse, like conventional greenhouses, energy must be consumed.

The difference is that the high-quality envelopes of a high-performance greenhouse opens doors for more advanced and more passive energy conservation measures. One such example is with the use of air to ground heat exchangers.

**Earth and Air Heat Exchange in the Greenhouse**

An earth and air heat exchanger is broadly categorized as a heating and cooling mechanism using the ground as a source or sink. It is created by an arrangement of pipes in soil, with air blowing through this series of tubes using a fan.

The trademarked Ground-to-Air Heat Transfer, or GAHT, System for high performance Ceres greenhouses is a heating and cooling mechanism using air with fans and underground pipes. It works as a type of ground coupled heat exchanger for more energy-efficient heating and cooling. The thermal mass of the ground functions as a heat storage space.

The general concept is thousands of years old, including ancient Persians using desert domes over pits to collect dew-freezes and cool during the day. In the Middle Ages in Italy caves were used to pre-cool and preheat air before it entered a building (Asimakopoulos et al., 1996). The more current system of buried tubes creating and Earth-to-Air Heat Exchange system has a variety of names under which it can be found in literature, these are detailed in Table 4.

**Table 4:** *Acronyms for the GAHT*

| Acronym | Name |
| --- | --- |
| EAHE | Earth-to-Air Heat Exchanger |
| EAHX | Earth-to-Air Heat Exchanger |
| EATHE | Earth Air Tunnel Heat Exchanger |
| GAHT | Ground-to-Air Heat Transfer |
| GHE | Ground Heat Exchanger |
| HETS | Horizontal Earth Tube System |
| EAPHE | Earth Air Pipe Heat Exchanger |
| EPAHE | Earth Pipe Air Heat Exchanger |
| UTES | Underground Thermal Energy Storage |

In this Ceres greenhouse application, underground pipes are combined with the high efficiency greenhouse to extend the growing season. The soil functions as a battery. Air is pulled in from the top of the greenhouse canopy—in this case the inlet is located in the center of the North wall—blown through the GAHT pipes, and released in the corners of the South wall. The purpose of the GAHT is to function as a lower tech, more low-cost way of using thermal energy storage for air heating and cooling. It is a good way to help balance temperature fluctuations as a form of climate battery. Figure 1 shows the foundation of the GAHT in this study as the tubes were installed between the inlet and outlet manifolds.

This experimental study on an active research farm means that resulting performance metrics can potentially be applied to local controlled greenhouse agriculture, as well as other geothermal climate control options. This research also provides a foundation for future work looking at advanced controls in a greenhouse and programming fans for maximizing energy

**Figure 1:** *GAHT Construction Image*

efficiency and maintaining peak growing conditions. Figure 1 shows an image of the GAHT installation in the Fall of 2020.

For this research, the function of the GAHT has been separated into three cycles: charging, storage, and discharge. These terms stem from the idea of the GAHT as an earth battery.

The charging cycle for the heating season occurs when hot air at top of the greenhouse is pulled through the inlet pipe with the fan. This hot air then proceeds through the 18" northern manifold where it enters the smaller 4" sleeved corrugated pipes of the GAHT. As the air flows through the smaller pipes, the charging cycle continues. Higher temperature air is then disseminated through the pipes and slowly warms the soil around it. There should be a steady temperature increase in the soil up until its heat capacity is reached, where the temperature will plateau at what will then be considered the 'charged' state.

hen the fans are disengaged, the storage cycle begins. The storage cycle hinges on maintaining a steady ground temperature with as little energy input or loss as possible.

Discharge occurs when the underground air is then pushed up through the outlet pipes into the greenhouse to provide warmer air heated by the earth.

**Problem Statement**

Greenhouse conditions are variable, and during the heating season charging of the GAHT may take different lengths of time. This will also vary the rates of fan energy consumption. There may also be fluctuations in inlet temperature that impact whether charging is feasible, so the storage and discharge stages are important in determining their longevity.

In terms of practicality, farmers often have limited resources and busy schedules. If a greenhouse lacks automation, then knowing when to switch a GAHT on or off depending on inlet conditions could be a helpful tool to save time. When an automation system is in place, having a characterization of this specific GAHT system will be useful in creating the most effective and efficient sequence of operation possible.

**Research Questions**

1. What is the heat storage capacity of the GAHT during a typical heating season day?
2. Does latent heat exchange need to be measured to determine the performance of the GAHT?
3. How might the Coefficient of Performance of the GAHT be characterized?
    a. What is the daily COP when the GAHT runs constantly?
    b. What is the COP when the GAHT runs after greenhouse temperatures drift well off of the setpoint?
4. How long does it take to reach a relative charged plateau under different conditions?

**Limitations**

There are a number of limitations to this study. Some comparisons or projections may not be fully accurate for characterizing a GAHT system within a working greenhouse since this space changed operational levels during the time of data collection. This study was conducted using only test methods, and working with very basic tool sets. While the data is limited to one season, there will be a lot of points to look at, with readings every five minutes and each minute depending upon the sensors. Uncertainty is also compounded by sensor accuracy as well as overall outdoor variability. The greenhouse space is used for active instruction so additional variability of door openings, moisture from watering, and added plants can also contribute to temperature changes.

## Overview of the Document

This document will include a brief review of literature, an overview of research methodology, data from the study, and analysis as well as system characterization.

## Review of the Literature

The purpose of this literature review is to explain and define the Earth-to-Air Heat Exchanger (EAHE), its characteristics, and various monikers. Then, a background in EAHE performance and existing studies is presented. The context of experimental EAHE work conducted in a greenhouse will be the focal point. Afterwards, some review of experimental uncertainty and relevant data analysis will be presented to provide background justification in the following chapters.

### Earth-to-Air Heat Exchangers

Earth-to-Air Heat Exchangers, commonly shortened in literature to EAHE, use the ground as a heat source during the winter and a heat sink during the summer. This geothermal energy system uses soil and air instead of liquid to create a heat exchange system. They generally involve tubes buried in the soil and a fan mechanism to pump the air through for thermal storage (Jayadi et al, 2019). The GAHT is the formal trademarked name for the Earth-to-Air-Heat-Exchanger from Ceres Greenhouse Solutions. When looking at the GAHT system, it uses the earth as a space for energy storage.

### Performance of EAHE

Based on work by Chiesa and Zajch (2019), the applicability of Earth-to-Air Heat Exchangers was measured in North America. In this study the virtual inlet temperatures were measured hourly, and split into varying soil conditional with highest thermal diffusivity with heavy and damp soil, seeing thermal conductivity of 1.3 W/mK, and 0.865 W/mK when the soil was heavy and damp. Considering weather files, soil surface temperature parameters, and degree hour changes within coordinates, this study classified the Watauga and Ashe region of North Carolina as medium priority for heating, and very high priority for cooling, though any variations could impact these projections. No physical tests were done in or near the state of North Carolina, but applicability for EAHE was theoretically established (Chiesa et al., 2019).

One of the often-cited studies done on an EAHE within a greenhouse context was performed in India. Ghosal et al (2004) created a typical winter day based on data collected and a computational model, showing expected hourly variation. The same was done for typical summer days. This work also emphasized the importance of greenhouse glazing and transmissivity in temperature conditions, and the impact of these factors on GAHT functionality for cooling. Based on Ghosal's (2004) research the earth battery system is more effective in winter. Their analysis used quasi-steady state conditions, and assumed uniform airflow along the length of buried pipes. They also assumed no radiative heat exchange between buried pipes for thermal analysis calculations. With a side-by-side greenhouse comparison, this study found a 6-7°C temperature rise for the greenhouse coupled with an operating EAHE. They found that enhanced glazing particularly improves the winter performance of a heat exchanger (Ghosal et al., 2004).

When narrowing in on greenhouse heating season, Bansal et al (2009) used modeling to do a performance analysis of EAHE for winter heating. Total hourly heat gain from the system varied from 423.36 to 846.72 kWh, and maximum hourly heat gain was observed at the air velocity of 5 m/s. The rise in air temperature was less at higher velocities, but the total heating effect per unit time was more.

**EAHE in Greenhouse Applications – Experimental Work**

An early experimental study done on a greenhouse with underground heat storage was done by Boulard et al (1989). This experiment consisted of PVC pipes as the tubes with a centrifugal fan to circulate greenhouse air, and looked at the heating season of the greenhouse in the South French Mediterranean at Avignon. This study looked at maximum and minimum temperatures throughout the heating season, measuring wet and dry bulb temperatures along with air flow rate and soil temperatures. They found soil thermal conductivity and heat capacity through mass transfer calculations. This study looked at enthalpy exchange at the entrances and exits of the pipes to calculate overall heat exchange. It focused more on diurnal dehumidification and nocturnal humidification from the tube system, and this impact in addition to temperatures on a tomato crop. The average total heat power in the working period was 95 $W/m^2$ for storage and 48 $W/m^2$ for night extraction. Latent heat represented 30% of the heat exchanges. Overall, this study shows that psychrometric measurements can calculate both sensible and latent heat exchange.

Yildiz et al (2012) looked at greenhouse cooling and energy performance of a GAHT-like system supported by photovoltaics in a greenhouse. The greenhouse, located in Turkey, had a horizontal u-bed earth-to-air heat exchanger and was glass reinforced plastic. They only did one day of testing for 11 hours. Based on this study the average rate of heat discharge was 5.02 kW with a 0.7 kW fan, and the average temperature difference between the inlet and outlet of the system was 8.29°C.

Ozgener & Hepbasli (2005) collected temperature data from throughout an underground EAHE in a greenhouse heating context while running the system at a steady state to conduct exergy analysis on destruction, efficiency and losses. This study determined that low efficiency components of the system can cause poor thermal performance. Their analysis showed the majority of system energy loss attributed directly to the pipe and the blower of the EAHE.

Table 5 below shows a substantive review of literature available regarding GAHT-like technologies.

**Table 5:** *Review of Relevant Literature*

| Authors | Type of Study | Topic | Summary of Relevant Findings |
|---|---|---|---|
| (1989) Boulard et al. | Experimental | Heat and vapour transfer in a greenhouse with an underground heat storage system | Maintained an average night inside-outside temperature difference of 7-9°C in March-April<br>Auxiliary heating to maintain the desired air temperature only 20% of the whole heating season requirement |
| (2004) Ghosal, M. K., Tiwari, G. N., & Srivastava, N. S. L. | Experiment-based Modeling | Experimental validation of thermal modeling with a greenhouse integrated EAHE | Greenhouse air temperatures were an average 6-7°C more in winter and 3-4°C less in summer |
| (2005) Ozgener et al. | Experimental | Experimental investigation of the performance of a solar-assisted ground-source heat pump system for greenhouse heating | BHE in greenhouse context at 50m depth<br>At the end of a sunny day the heating COP of the heat pump was almost 2.84, while it was 2.13 for a cloudy day |
| (2006) Tiwari et al. | Experimental | Annual thermal performance of greenhouse with an earth-air heat exchanger: an experimental validation | Validates Ghosal's thermal model<br>Non-operational hours of an EAHE are 252 and 279 for February and March months, respectively.<br>Finds a maximum value of heating potential (11.55 MJ) and cooling potential (18.87 MJ) |

| | | | |
|---|---|---|---|
| (2009) Bansal et al. | Modeling | Performance analysis of earth–pipe–air heat exchanger for winter heating | Annual energy saving potential of EAHE with performance analysis<br>Model able to use computational fluid dynamics to predict thermal performance and heating capacity |
| (2011) Ozgener et al. | Experimental | Experimental prediction of total thermal resistance of a closed loop EAHE for greenhouse cooling system | Average total heat exchanger thermal resistance was estimated to be 0.021K-m/W as a constant value under steady state condition |
| (2012) Yildiz et al. | Experimental | Energetic performance analysis of a solar photovoltaic cell (PV) assisted closed loop earth-to-air heat exchanger for solar greenhouse cooling: An experimental study for low energy architecture in Aegean Region | Average temperature differences between inlet and outlet of earth-to-air heat exchanger 8.29°C at measurements |
| (2013) Darkwa et al. | Simulation | Heat dissipation effect on a borehole heat exchanger coupled with a heat pump | Annual average energy lost into the soil was almost 4.5 times higher than the amount extracted, decreasing the heat storage capacity of the surrounding soil |
| (2013) Misra et al. | Experimental | Transient analysis based determination of derating factor for earth air tunnel heat exchanger in winters | Under steady state condition, a rise of 19.6°C is obtained in air passing through EAHE having 0.1m diameter and 60m length (at 5 m/s flow velocity)<br>Transient analysis shows that for soil having thermal conductivity 0.52 W/m-K, the heating of air reduces from 19.4°C to 17.2°C, after 24h of operation.<br>Heating effect after 24h of operation for soil thermal conductivity of 2.0W/m-K |

| | | | |
|---|---|---|---|
| | | | and 4.0 W/m-K, reduced from 19.6°C to 19.2°C and 19.6°C to 19.5°C respectively |
| (2013) Mongkon et al. | Experimental | Cooling performance and condensation evaluation of horizontal earth tube system for the tropical greenhouse | Demonstrated that the EAHE was capable of cooling up to 74.84% in the summer<br>For condensation inside HTES, the operation of the blower was an additional advantage to eliminate the water condensation after cooling |
| (2014) Lanini et al. | Experimental | Improvement of borehole thermal energy storage design based on experimental and modelling results | Injection during a day of 95% of the collected solar heat into the ground through a Borehole Heat Exchanger (BHE) with a 180 m depth rapidly dissipated into the ground.<br>Applying a single BHE in the ground shown inefficient for either day/night or inter-seasonal underground thermal energy storage |
| (2014) Vaz et al. | Experimental | An experimental study on the use of Earth-Air Heat Exchangers | Based in Brazil, found based on transient behavior of temperature fields for the external air, soil and buried ducts and the best periods for heating and cooling deployment were May and February |
| (2015) Bisoniya et al. | Experimental | Computational Fluid Dynamics looking at building heat reduction in India, a heating season EAHE design | Minimum air temperature rise of 8.2°C for airflow at 2 m/s and 6.8°C for airflow at 5 m/s<br>Hourly heating potential ranged from 0.59 to 1.22 MJ h, with air flow velocity greatly impacting thermal performance<br>Declining temperatures throughout the heat exchanger |

| | | | |
|---|---|---|---|
| | | | as air moves through the system |
| (2019) Chiesa et al | Modeling | Geo-climatic applicability of earth-to-air heat exchangers in North America | Increased depths appear to have diminishing returns past 2.5–3 m.<br>EAHE systems are less sensitive to soil thermal properties and surface conditions<br>EAHE systems best suited for temperate climates where there is a balance in heating and cooling needs |
| (2020) Ł. Amanowicz & J. Wojtkowiak | Experimental | Thermal performance of multi-pipe earth-to-air heat exchangers considering the non-uniform distribution of air between parallel pipes | Winter-time summing temporary heat gains on an hourly basis<br>Calculated the Nusselt number of the internal pipe wall<br>Showing airflow temperature distribution with a visible depiction of changes in uniformity |
| (2020) Congedo et al. | Modeling | Numerical and experimental analysis of the energy performance of an air-source heat pump coupled with a horizontal earth-to-air heat exchanger in different climates | Seasonal energy efficiency ratio |
| (2020) Kumar et al. | Review | Development of Passive Energy Source as Earth Air Pipe Heat Exchangers System | Thermal conductivity of the soil is the key point to the efficient operation of the earth air pipe heat exchanger system<br>Most notable change occurred in evaporative temperature when air velocity was varied – increased velocity results in a low-temperature gradient between inlet and exhaust air |

| | | | |
|---|---|---|---|
| (2020) Sakhri et al. | | Effect of the pipe material and burying depth on the thermal efficiency of earth-to-air heat exchangers | Recommended burying depth of 80-150 cm<br>Advantages of PVC over steel pipe for earth to air heat exchangers<br>Pipe length largest impact on performance (none corrugated) |
| (2021) A. Minaei & H. Safikhani | Modeling | A new transient analytical model for heat transfer of earth-to-air heat exchangers. | 3D numerical model and Laplacian transform, with 0.87% to 0.4% discrepancy between the analytical model and reported experimental results |
| (2021) Qi et al | Modeling | Numerical Assessment of Earth to Air Heat Exchanger with Variable Humidity Conditions in Greenhouses | Standard deviation increase of 49% when the inlet air volume flow rate was almost doubled<br>Inlet air temperature influenced the integrated performance of the EAHE |
| (2021) Wei et al. | Experimental | Hot-summer and cold-winter area, using the heat exchanger for both heating and cooling | Indoor environment not greenhouse<br>For winter months found a soil temperature variation within 11.71-12.01°C at a depth of one meter.<br>Outlet air could obtain an increase of 5.53°C compared to inlet temperature in the winter |

Overall, no formal research has been conducted on the performance of a GAHT, or GAHT-like system in the Appalachian Mountains, or North Carolina more generally. This research documents GAHT performance in the unique climate of the region. Most studies are conducted in more arid climates, within the context of building structures rather than a high-performance greenhouse. Table 6 shows the variety of modeling approaches used so far. No published work looks at greenhouses with the efficiency of the Ceres greenhouse of this study, and the majority are not experimental. This study provides some missing experimental characterization of an operational greenhouse in the winter.

**Table 6:** *Modeling Approaches for Study*

| Modeling Approach |
|---|
| Numerical Model in TRNSYS |
| 3D Numerical Model Simulation |
| Laplacian Transform from Transient State |
| Computational Fluid Dynamics |
| Thermal Load Leveling Calculations |
| EAHX geo-CLImatic Potential Script |

**Coefficients of Performance & Mini Splits**

When looking at heating performance in ventilation, the coefficient of performance (COP) is a standard metric to quantify the thermal efficiency of the system as heat converted to work. One commonly used system in building heating is a mini split heat pump. (Roth et al, 2013). These are often used as retrofits or upgrades to improve heating efficiency in a ductless scenario. The typical heating COP for a mini split system can range from 2-5, with 2 as a starting adequate performance point (Winkler, 2011).

The COP is calculated by looking at the useful heat supplied or removed versus the energy needed to run the fans. This can be done with the following formula where Q is the energy transferred through the GAHT, and W is the work done or the energy needed to drive the fan. Equation 1 shows the formula to calculate the Coefficient of Performance.

$$\boldsymbol{COP = \frac{Q}{W}} \tag{1}$$

**What are reasonable methods to analyze this type of data**

Based on this previous literature, modeling is a primary form for analysis of EAHE systems. However, when looking at the calculations and experimental design, each study includes data on flow rates, temperature, and humidity. Many specify various starting conditions or parameters of the experiment.

For this study, psychrometric calculations for change in enthalpy throughout the system will be the primary form of analysis to find heat storage quantities. The ASHRAE Handbook of Fundamentals provides all formulas for psychrometric calculation procedures. Coefficients of Performance also help to characterize the system and define efficiency.

To apply experimental uncertainty analysis to the planned research in this study, all elements of measurement will be combined for a compounded uncertainty. The expected uncertainty can be found using the root of the sum of the squares of the uncertainty to derive experimental uncertainty (Cimbala, 2013). Equation 2 shows the compounding uncertainty calculation.

$$\boldsymbol{U = \sqrt{\sum_{i=1}^{i=N} (U_{x_i} \frac{\partial R}{\partial x_i})^2}} \tag{2}$$

This research should find associations between certain inlet conditions and GAHT characterization during the heating season.

# Methods

Broadly speaking, this research is done using quasi-experimental design. In the methods, an overview of the experiment site is provided, the specific research apparatus is described, sensor layout and measurement uncertainties are presented, a general psychrometric approach to contextualize GAHT operation in terms of energy is detailed, and methods to address each question are laid out. The methods for answering each question include descriptions of data acquisition protocols, preprocessing steps, and data analysis structures.

## Description of Experimental Site and Climate

The Ceres Greenhouse in this study is located on Appalachian State University's Blackburn-Vannoy (BV) Farm. Figure 2 shows a map of the site of the BV Farm and Figure 3 gives a satellite image of the farm property. The greenhouse has a GAHT system which is meant to geothermally regulate this high efficiency greenhouse temperature and to a lesser degree humidity. The Appalachian State BV Farm falls under the protection of the Blue Ridge Conservancy. This area is part of ASHRAE Climate Zone 5A, a region with between 5400 and 9000 heating degree days. The PV Watts average annual solar radiation for this area is 4.98 $kWh/m^2/day$ for a surface facing due South. A typical greenhouse in this area will have a heating season ranging from November through March or April, though many farmers will stop growing in December through February as temperatures are too low. This is the period that is considered

**Figure 3:** *Location of Appalachian State University BV Farm and site of research*

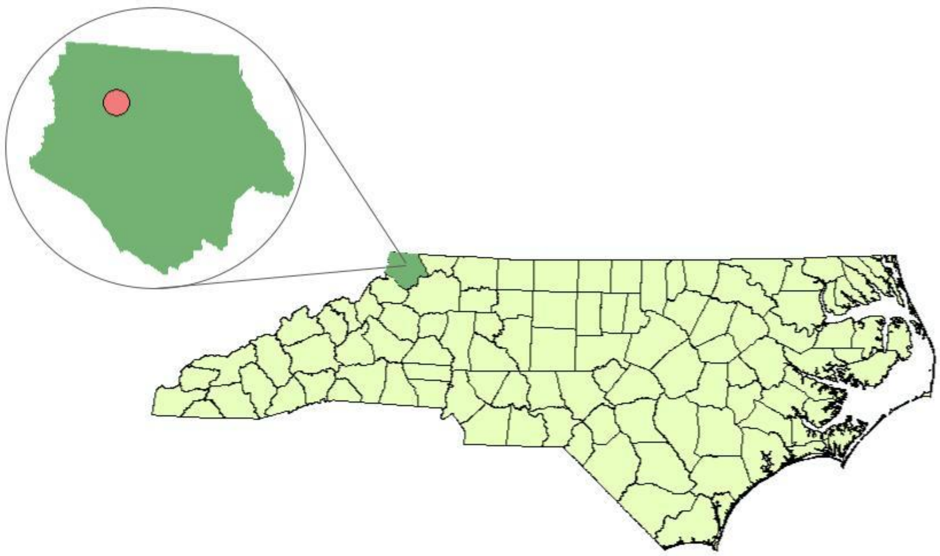
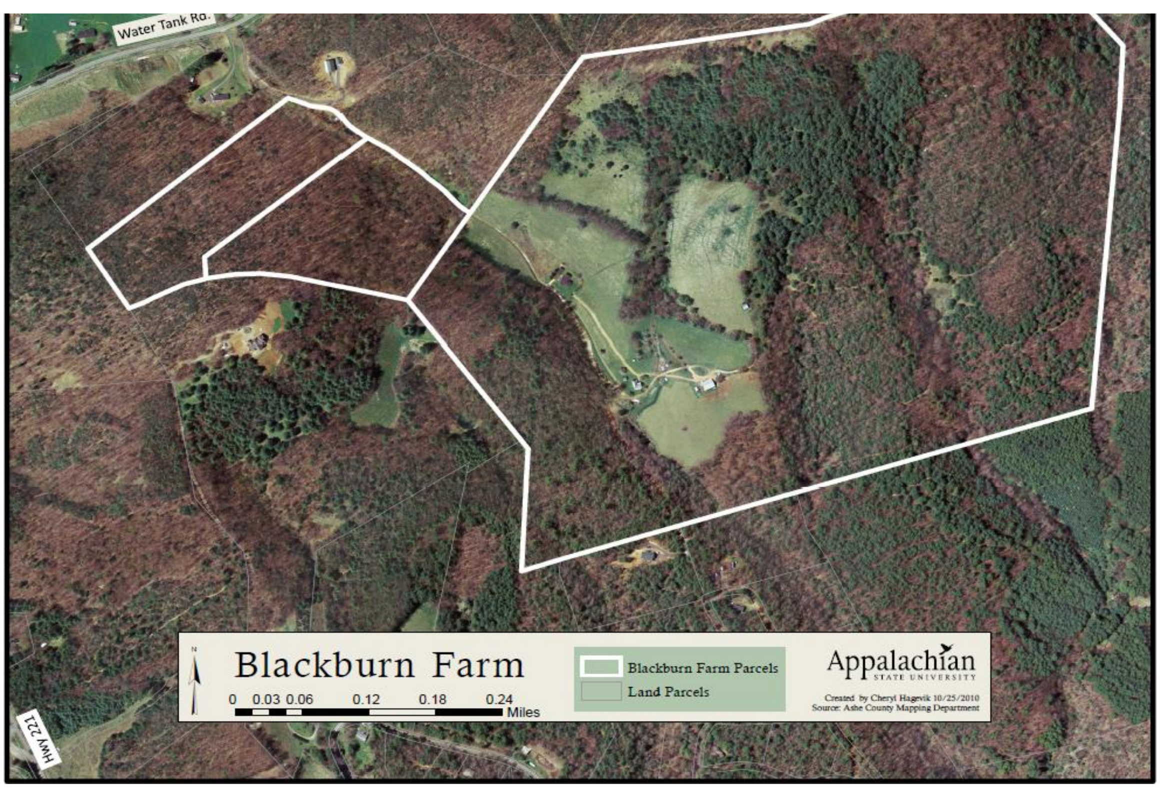


**Figure 2:** *Satellite Map of BV Farm property where research site is located*



for this work. Table 7 shows the average climate data for the month of February in the region of study.

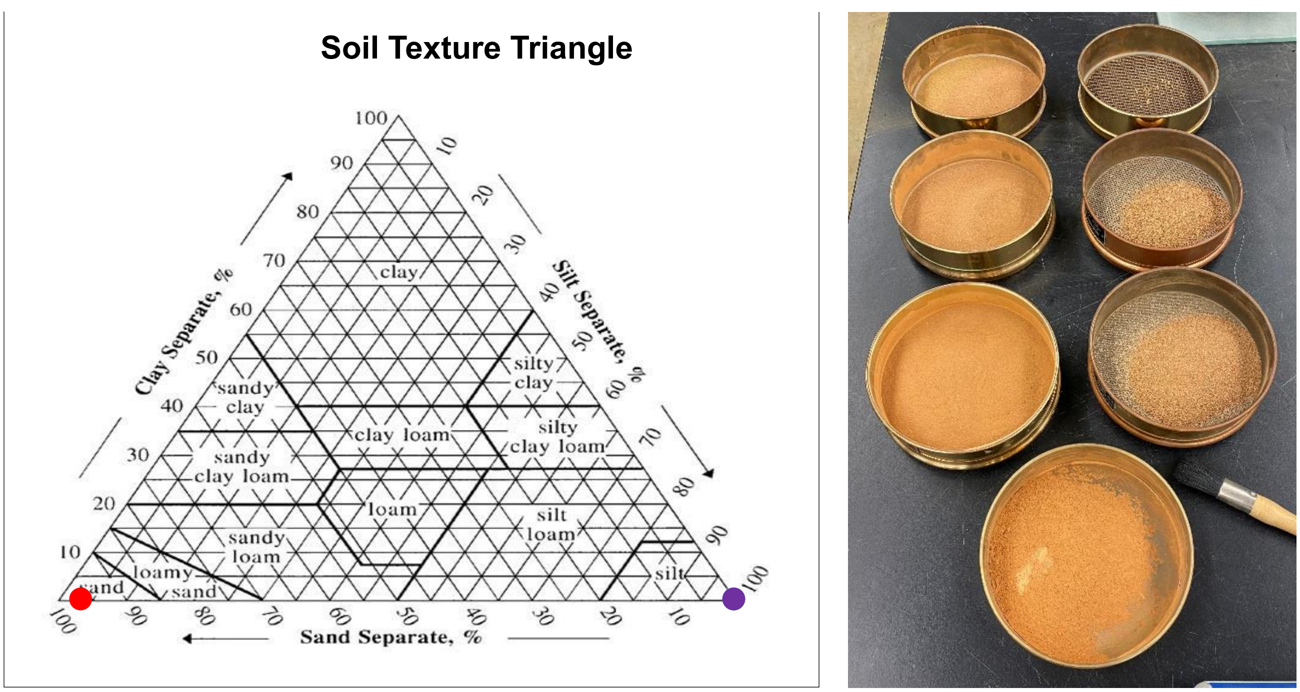
**Table 7:** *Regional Climate Averages for Winter Month of Study*

| February Climate & Weather Averages in Ashe County (from past 10 years climate data) | | |
|---|---|---|
| High Temp: 45°F | Precipitation: 1.80” | Wind: 9 mph |
| Low Temp: 27°F | Humidity: 59% | Pressure: ~29 inHg |
| Average Temp: 36°F | Dew Point: 21°F | Visibility: 9 mi |

**Soil Type**

The soil for the location of this GAHT system is majority sand with only 3.35% clay or silt content. The thermal conductivity value average for the soil in the GAHT is 0.27993 Watts per meter-Kelvin at 12.1% water content. This means that this soil has relatively low thermal conductivity, which may impact GAHT function. The soil sample was taken from beside the greenhouse, and the conductivity measure was taken within the ground inside the greenhouse.

**Figure 4:** *Soil Texture Classification of Greenhouse Soil & Soil Sample Detail*



The GAHT fill came, in part, from another location on the farm. This was used first to fill the deeper portions of the East side of the GAHT. Figure 4 shows the soil texture triangle for the soil sample classification as sand, and the sieves for this classification process.

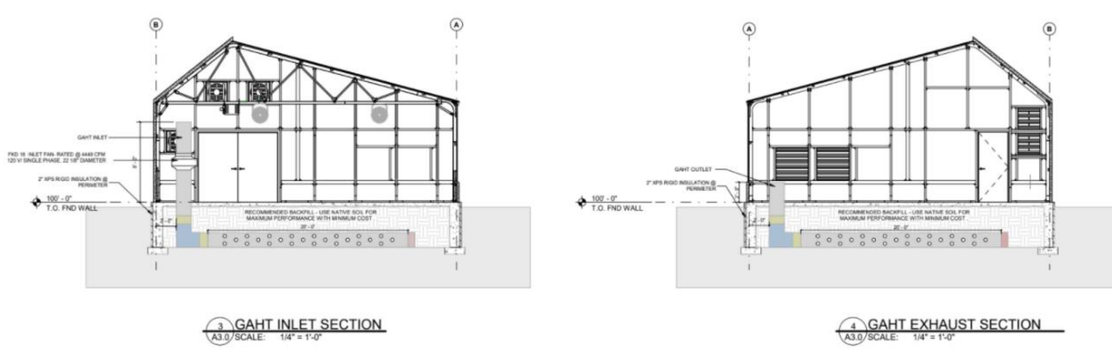
## Description of the Research Apparatus

The GAHT is installed below a high efficiency greenhouse, which at the time of this study just finished final construction.

### Greenhouse Characteristics

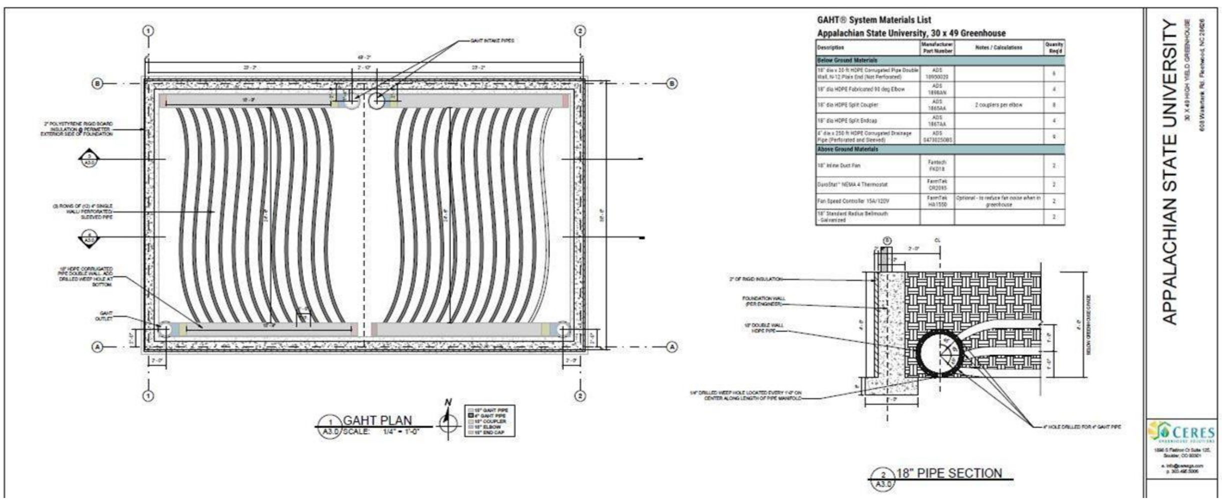
The Ceres high efficiency greenhouse in this study is run by the farm manager for Appalachian State University. It is 30 feet by 49 feet, and its peak is just under 16 feet, with 10-foot eaves at the North and South walls. It is rated for a wind load of 130 mph and snow load of 20 psf. The frame is a steel construction, with 16 mm polycarbonate that fits into tracking built into the frame. The non-glazing walls of the greenhouse are made of all-weather insulated panels. Their R value is 20 or 24 depending on the ribbing, and are prebuilt with fastening systems for tightness with a steel shell. Figure 5 shows a representative design engineering detail of the Ceres Greenhouse in this study with the GAHT system below.

**Figure 5:** *Ceres Greenhouse Construction Detail with GAHT below*




In this GAHT design there are thirty-six pipes below the ground, thirteen of which are outfitted with temperature and relative humidity sensors for general data collection. The inlet and outlet pipes are also outfitted with temperature and relative humidity sensors for the calculations in this study. Of the smaller tubes, each pipe is approximately 26 feet in length, with the sensor pipes cut at 24 feet to fit into the wye connectors for instrumentation access. The smaller tubes are corrugated, perforated, and have sleeves for drainage and soiling protection. A construction detail for the GAHT tubes and manifolds is shown in Figure 6.

**Figure 6:** *Construction Detail of GAHT piping and manifold system*




Attached to the two 18” inlet manifolds are two Fantech FKD 18 inline centrifugal fans. These operate at 120 Volts, and are made of galvanized sheet metal on the outside with a plastic curved impeller on the inside. For these fans the speed is not able to be remotely programmed. For the purposes of this experiment the fans were run at 100% for varying periods of time.

To get the flow rate of the fans, for the outlets a calibrated fan from a blower door setup was adapted over the outlet tube. The West outlet was measured on two occasions and indicated a flow of 2800 CFM. The East outlet also indicated a flow of 2800 CFM consistent with the repetitions. In addition, the static pressure drop across both FKD18 fans was measured. The pressure drop was 1.12” water gauge for the West and 1.2” water gauge for the East.

Measuring the static pressure drop across the inlet fans allowed a conversion from Pascals to inches water gauge which could be plugged into the fan curve. The change in pascals was converted to change in water column, which can then define flow in cubic feet per minute. When the static pressure drop was compared to the manufacturer fan curve a flow of 3000 CFM was projected for the West fan and 2900 CFM for the East fan. As seen in Figure 7 below for the fan curve, the curve data was provided by the fan manufacturer, and a polynomial fit applied to plug in the inches water gauge value to determine flow. Table 8 provides the specifications for the FKD18 fan.

**Table 8:** *FKD18 Fan Specifications*

| Fan Specs (FKD 18) | |
|---|---|
| Volts | 115 |
| Watts | 1440 |
| Hz | 60 |
| Amps | 12.8 |
| Air Flow | max 4,448 cfm |
| Max Temp | 60°C |

The greenhouse operational parameters during this winter study seek to keep the temperature around 55°F or 13°C to get a clearer idea of potential GAHT performance, and relative humidity below 90%. The greenhouse should not go over 85°F or 32°C as this will damage the plants. For the purpose of this experiment, binning of inlet conditions will be necessary as data is collected.

**Figure 7:** *Graph of the FKD18 Fan Curve*

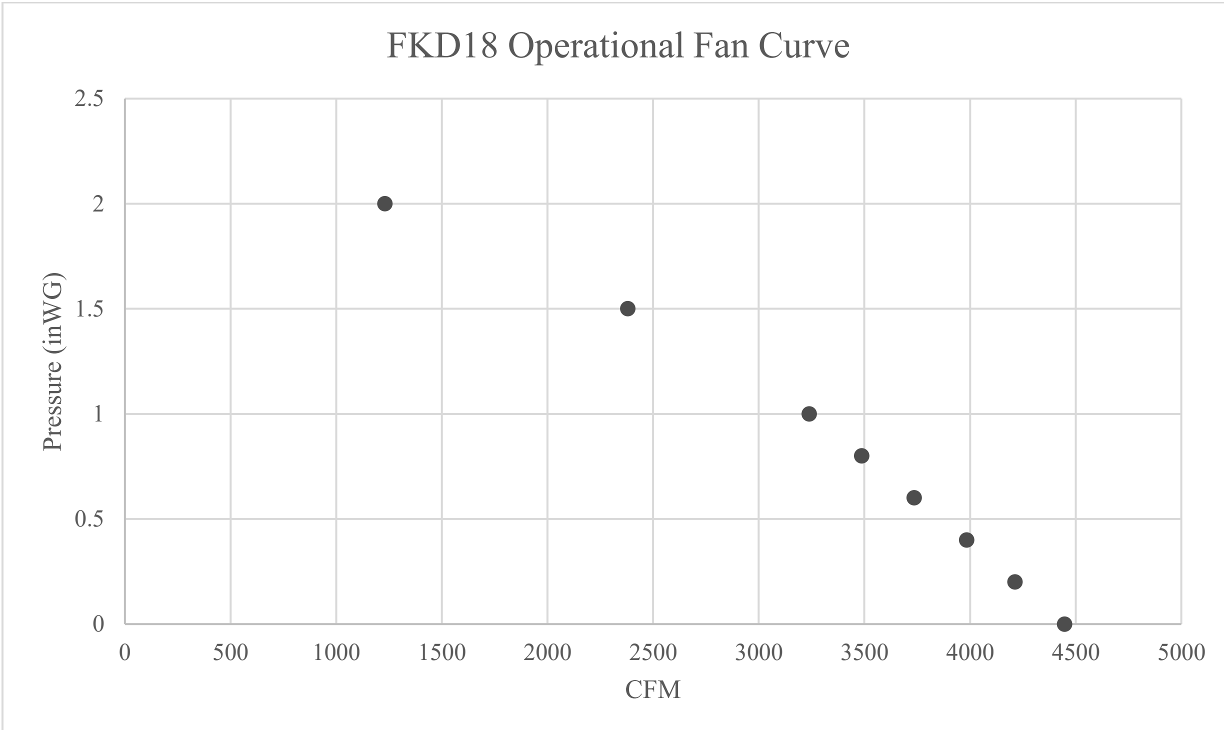


Figure 8 shows the process for the calibrated fan attachment to the GAHT outlet pipe for cubic feet per minute measurements.

**Figure 8:** *Image of Calibrated Fan setup for flow measurements of the GAHT*

To do research on this system two large fans are connected to the center manifolds, and then the function of the GAHT pipes is measured through the reaction of temperatures and relative humidity levels within the GAHT. The sensor setup for this experiment is the following: For the bulk convective heat transfer calculation numbers there are temperature and relative humidity sensors in both the inlet and outlet pipes. An atmospheric pressure sensor is located near the center of the North wall. The primary soil sensor run through the ethernet-connected

HOBOlink system was installed with a 2” hand auger in the center of the greenhouse for long term monitoring in future data collection. A differential pressure sensor (DG1000) was used to verify flow after conducting the calibrated fan analysis.

**Figure 9:** *Image of GAHT Fans alongside the Sunsense Controls Box*


**Greenhouse Control Strategies**

The sequence of operation depends on whether the GAHT is working to cool or heat the greenhouse. For these purposes, the study only looked at the heating season during winter. After running the system for a couple weeks to reach an equilibrium point and clear any environmental debris including spiders from the system from construction and inactivity, the main data collection for this project began. Figure 9 shows the fans in the center of the north wall of the

Ceres greenhouse alongside the Sunsense box which is where all of the GAHT and greenhouse climate controls and sensors connect. The wires for the inlet temperature and relative humidity sensors for this study are also visible. The sensors for the Sunsense controls system are located at the center of the greenhouse.

This GAHT system when operational will turn on when the temperature in the greenhouse reaches higher thresholds during the middle of the day. The point at which this threshold is reached will vary depending on variable outside conditions and irradiance levels. Ceres implements a combination of stages in their greenhouse system.

Tables 9 and 10 show the actual control strategies used for this characterization study. These are based on temperature setpoints, action is triggered when the temperature is a certain delta above or below the setpoints to initiate responses. For cooling the GAHT turned on at 76 degrees Fahrenheit, and for heating the GAHT turned on when temperatures dropped to 55 degrees Fahrenheit. The Operations Manual Ceres recommended Sunsense automated heating control stages are listed in Table 11 below. These were adapted for this study to make sure the GAHT was running more, and to fit the working greenhouse operations.

In the context of this research the greenhouse auxiliary propane heaters did not kick on as their connections were not in place and it would take away from GAHT data. For the listed automated controls, the stages are sequential when moving from one to four and one to eight, however they then lock in at highest stage until the first stage conditions are reached again. The control state depends on the history, or looking at whether the temperature to setpoint Delta is increasing or decreasing. The automated system uses a combination of Senva and Honeywell controls and measurement devices, programmed by Ceres Greenhouse Solutions.

**Table 9:** *Cooling Control Strategy (based on °F)*

| Stages | EN | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Offset | | +2 | +6 | +10 | +12 | +13 | +14 | +16 | |
| GAHT East | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| GAHT West | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Exhaust Fan 24" A | ■ | | | | ■ | ■ | ■ | ■ | ■ |
| Exhaust Fan 24" B & Louver A | ■ | | | | | | ■ | ■ | ■ |
| Exhaust Fan 24" C & Louver B | ■ | | | | | | | ■ | ■ |
| Circulation Fans | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

**Table 10:** *Heating Control Strategy (based on °F)*

| Stages | EN | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Offset | | -9 | -10 | -15 | -20 |
| GAHT East | ■ | | ■ | ■ | ■ |
| GAHT West | ■ | | ■ | ■ | ■ |
| Heater East | ■ | | | ■ | ■ |
| Heater West | ■ | | | ■ | ■ |
| Circulation Fans | ■ | ■ | ■ | ■ | ■ |

**Table 11:** *Recommended Automated Control Settings for Ceres Greenhouse in Operations Manual*

| Ceres Greenhouse Heating Stages | | | | |
|---|---|---|---|---|
| Equipment | Stage 1 (15.6°C) | Stage 2 (13.9°C) | Stage 3 (11.7°C) | Stage 4 (10.0°C) |
| Heater A | | ON | | |
| Heater B | ON | ON | | |
| GAHT-1 | | | ON | |
| GAHT-2 | | | | ON |

## GAHT Data Acquisition

The data for this study is acquired through a variety of channels. The main measurements are taken through an ethernet-connected HOBO logger. For the underground GAHT tubes there is manual collection from a CSV file saved to an SD card on the ArduinoMega in the greenhouse. There are Bluetooth HOBOlink sensors, as well as a battery-powered HOBO Data

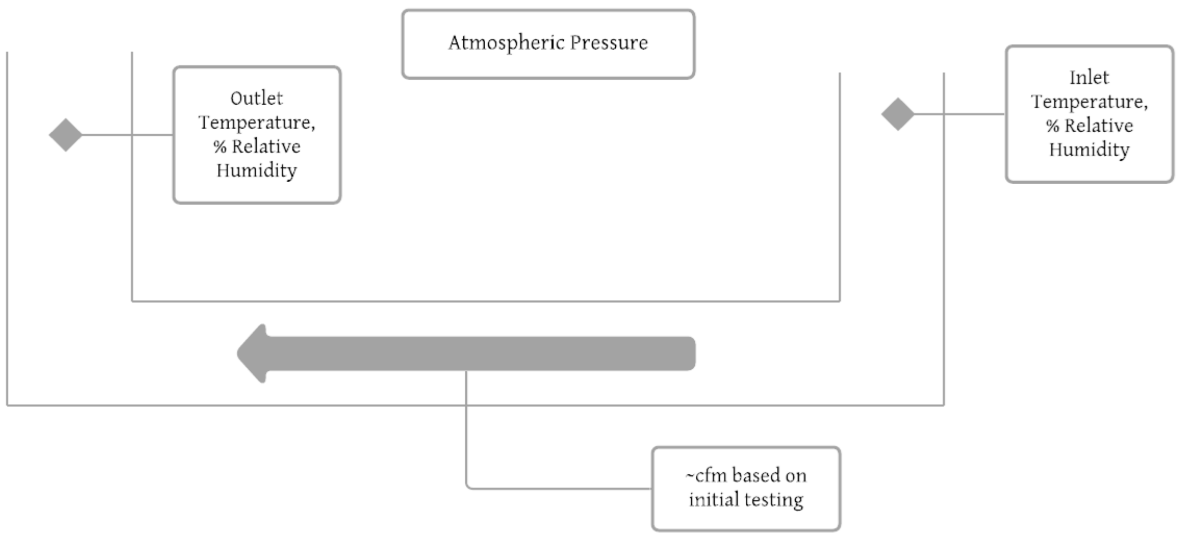
Logger for backup soil sensors and HOBO sensors for the inlet and outlet pipes and their temperature and relative humidity levels. This is all compiled into Microsoft Excel. Through bulk convective heat transfer and coefficient of performance calculations the data was then analyzed alongside greenhouse and outdoor conditions.

For quality assurance and control of the GAHT initial testing began once electricity and ethernet were installed for the primary sensors in this study, the remote HOBOlink data could be accessed for analysis of COP and enthalpy. The HOBO temperature and relative humidity sensors at both inlets and outlets in addition to the HOBO atmospheric pressure sensor were the key measurement points for this research. Table 12 details each of the sensors used in this study, and Figure 10 shows the locations of the primary measurement sensors used.

**Table 12:** *Sensor Details*

| Sensor Type | Model # | Accuracy | Precision/Resolution | Operable Range |
|---|---|---|---|---|
| Barometric Pressure | S-BPB-CM50 | ±3.0 mbar (0.088 in. Hg) over full pressure range at 25°C (77°F); maximum error of ±5.0 mbar (0.148 in. Hg) over -40° to 70°C (-40° to 158°F) | 0.1 mbar (.003 in. Hg) | -40° to 70°C (-40° to 158°F) 660 to 1070 mbar (19.47 to 31.55 in. Hg) |
| Blower Door Calibrated Fan | DG-1000 | 0.9% of pressure reading or 0.12 Pa, whichever is greater | +/- 3% | |
| HOBO Temperature Relative Humidity | HOBO U10 | ± 0.53°C (1.8°F) | ± 3.5% | 0° to 50°C (32° to 122°F) |
| Arduino Temperature & Relative Humidity | TSC200 | ±2% | | |

**Figure 10:** *Primary GAHT Measurements and Sensor Location for Energy Quantification*




**Experimental Procedure**

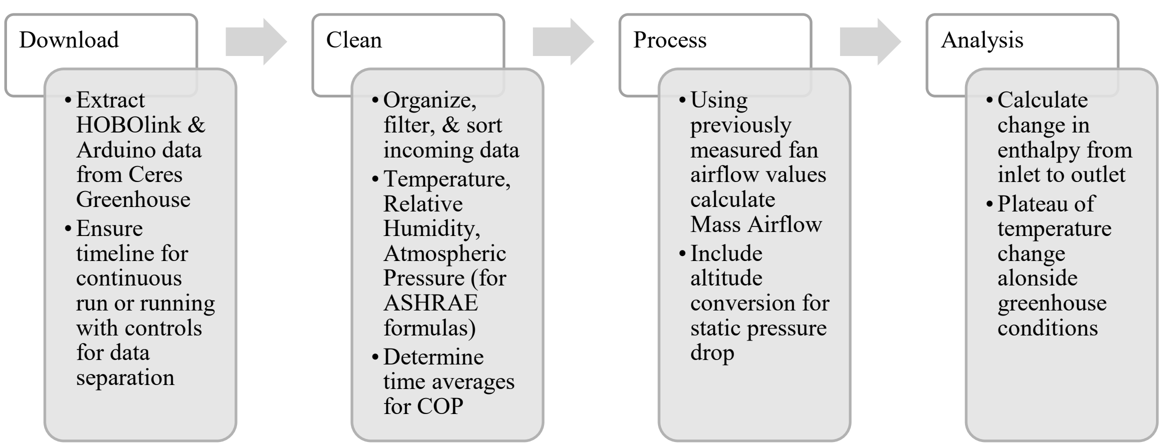
For this experimental design, the GAHT system was run over the course of the winter month of February, first continuously and then with its installed controls. The treatments are a continuous run, and then running the system limited by the GAHT controls. Supplemental analysis will seek to find the longevity of a charged GAHT, to see how long the ground maintains its temperature without air influx. This is based on an assessment of the GAHT Coefficient of Performance and to quantify the total possible energy stored.

The key variables involved are the energy, both from the fan to push air in, as well as energy in terms of heat being stored in the ground. This relates to temperature and relative humidity, as these show the sensible and latent energy of the GAHT. Through bulk convective heat transfer, the heat storage of the system can then be quantified based on different starting conditions.

Mass flow was determined from the fan characterization procedures detailed above. To get flow numbers for enthalpy calculations, the blower door calibrated fan sat above the outlet pipe, pulling the air out. The calibrated fan has a pressure sensor which can be connected at the outside as well as at the outlet itself. This pressure difference needed to be the same as the room (pressure difference zero) and the fan must sometimes be sped up to achieve this. Whatever the speed of the calibrated fan was the flow rate that the inlet fan was producing. A small amount of pressure loss is to be expected as there may be air loss throughout the system. There were about 4 BTUs difference from the inlet to outlet, looking at approximately 5% error.

With the data gathered, enthalpy calculations for the inlet and outlet provide a numeric difference in energy. These numbers plus fan data also provide the basis for COP calculations. Figure 11 shows a process flow from getting the data through its analysis.

**Figure 11:** *Process flow of experimental data work*




**Data Processing**

Another factor to consider in looking at the data from this study are the temperature and altitude effects on fans. For this work the equations include an altitude conversion factor for the static pressure value since the greenhouse is located above sea level. To do this, the static pressure drop must be multiplied by 1.14 to bring it to what it would have been at sea level. This is to convert every inch of water column to 1.14" for elevation.

Regarding the heat storage of the GAHT, this was found by solving for enthalpy in versus enthalpy out shows the energy—or heat—transferred to the soil. By running the GAHT and measuring bulk convective energy exchange, the system could be run until change in enthalpy neared zero difference from inlet to outlet. Dependent on varying starting points along with the end point. Given the dry bulb temperature and percent relative humidity numbers measured, the enthalpy of the system is also calculated using the psychrometric chart.

**Energy Quantification & Calculations**

With the data collected, both the inlet and outlet measurements are then put through a series of calculations to quantify the specific enthalpy on both ends of the system.

First, calculate Saturation Vapor Pressure using the ASHRAE Handbook of Fundamentals First Chapter formula 5. Equation 3 shows the saturation vapor pressure calculation.

$$P_{WS} = 145.03774 \left[\frac{2C}{-B + (B^2 - 4AC)^{0.5}}\right]^4 psia \quad \textbf{(3)}$$

Using the results from the previous equation, plug Saturation Vapor Pressure ($P_{WS}$) into the ASHRAE Handbook of Fundamentals First Chapter equation 22 to find the Saturation Humidity Ratio. Equation 4 shows the saturation humidity ratio calculation.

$$W_S = 0.621945 \frac{P_{WS}}{P - P_{WS}} \quad \textbf{(4)}$$

Using the Saturation Humidity Ratio and % Relative Humidity measurement from the greenhouse, find the Actual Humidity Ratio. Equation 5 shows the humidity ratio calculation.

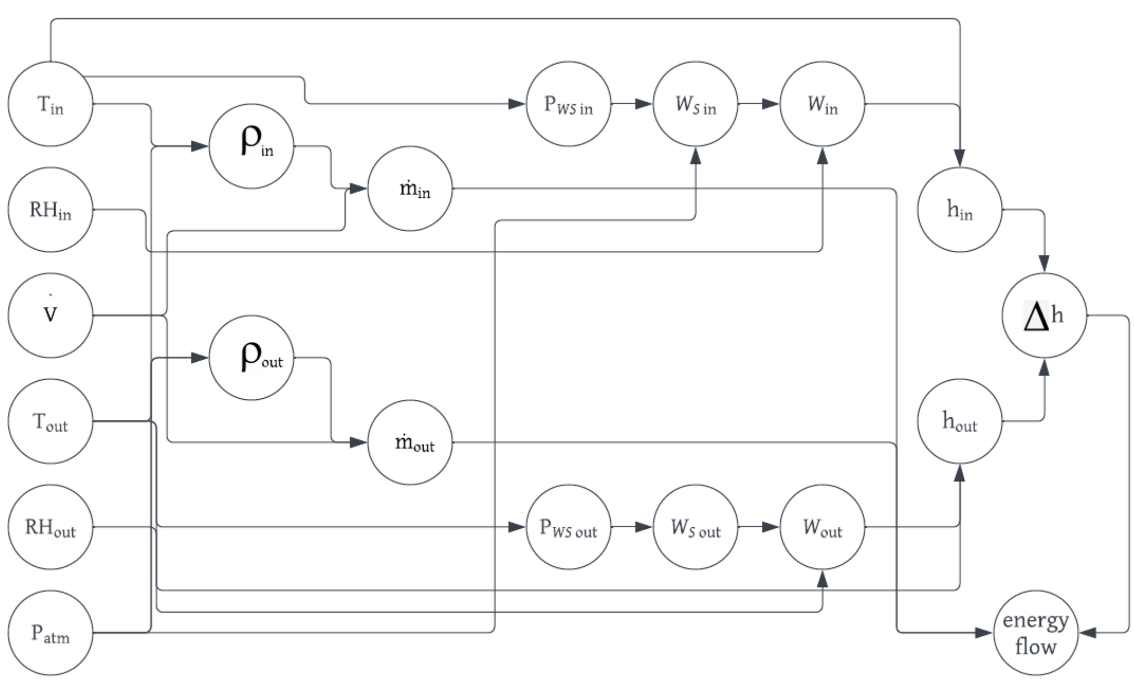
$$W = W_S \times \%RH \quad (5)$$

With the temperature reading and actual humidity ratio, calculate the specific enthalpy using the ASHRAE Handbook of Fundamentals First Chapter formula 32. Equation 6 shows the specific enthalpy calculation.

$$h = 0.240t + W(1061 + 0.444t) \quad (6)$$

Given the enthalpy values $h$, the delta value or difference in enthalpy from inlet to outlet is the heat energy lost (or 'stored') in the system. For the purposes of this study, the temperature change is positive when energy is going into the ground, and negative when the energy is going into the greenhouse. The outlet enthalpy is subtracted from the inlet, so that energy going into the GAHT results as positive energy flow. Figure 12 shows how all of these variables interact on the way to finding the total energy flow.

**Figure 12:** *Measurements and Psychrometric Calculation Value Flow for results and compounding uncertainties*



The Coefficient of Performance (COP) calculations then use the BTU energy exchange rate and fan data.

**Experimental Variability and Uncertainty Analysis**

For this data analysis, experimental uncertainty must be applied to the calculations. Both random and systematic uncertainties occur in this research, and including this compounding factor in the ASHRAE calculations shows its impact. To calculate the uncertainty of the result values, each time a measurement is included in one of the formulas to reach enthalpy, a derivative function must be performed. This only accounts for random errors. Figure 12 from the previous section shows each of the measurements and variables involved in these psychrometric calculations, and how the uncertainty is compounded from the sensors through each of these paths. To calculate the uncertainty, the root of the sum of squares was performed for each variable to arrive at total energy flow uncertainty (Cimbala, 2013).

For the begin of this calculation, 3% of the maximum flow rate of 6500 CFM was used for the fan uncertainty assumption. The remaining uncertainty numbers are directly from the sensor spec sheets There is typically around 100 BTU/min uncertainty for this setup. Table 13 shows the propagated uncertainty values throughout the psychrometric calculations.

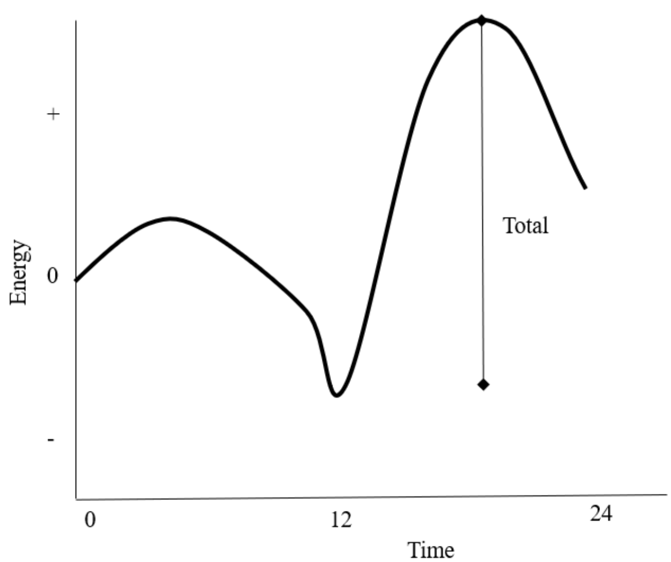
**Table 13:** *Uncertainty Values for Stages in Enthalpy Calculation*

| | |
|---|---:|
| Uncertainty of Inlet Air Density | 0.000235 lb/ft³ |
| Uncertainty of Inlet Mass Flow | 13.45 lb/min |
| Uncertainty of Outlet Air Density | 0.000237 lb/ft³ |
| Uncertainty of Outlet Mass Flow | 13.52 lb/min |
| Humidity Ratio Uncertainty | 0.000492 lb/lb |
| Inlet Enthalpy Uncertainty | 0.54 BTU/lb |
| Total Enthalpy Uncertainty | 110 BTU/min |

**Question 1 Methods**

To find the daily heat storage capacity of the GAHT for heating, the temperature difference each day from the energy minimum to maximum can be calculated using the enthalpy quantification. For this set data was only used from when the GAHT fans were continuously running, and conditions were partly cloudy or sunny to have higher delta values. Figure 13 gives a visual representation of this maximum to minimum threshold when looking at daily measurements. The slopes of the curve indicate whether the GAHT is charging (positive) or discharging (negative). The highest values for energy storage can be reached coming off of a cloudy day going into sunnier solar radiation conditions, which for this data set is looking at the 8th of February to the 9th.

**Figure 13:** *Graph showing a typical energy curve for the GAHT, and where the discharge point begins, rising up to the charging peak*



**Question 2 Methods**

To answer the second research question, it is a basic comparison of sensible versus total enthalpy exchange. To do this, a ratio of just sensible heat to total enthalpy was employed, using only the time period where GAHT controls are running and the GAHT is on. Sensible heat was calculated with the mass flow multiplied by the heat capacity multiplied by the change in temperature. This energy flow was then compared to the total enthalpy energy flow by looking at a basic ratio of the two values. If only sensible heat is necessary, the ratio would be 1. If the latent heat matters, then the ratio would deviate from 1. This ratio is based on the change in sensible energy per pound of air across the GAHT divided by the change in total enthalpy per pound of air across the GAHT. These numbers were not multiplied by mass flow to get total energy flow.

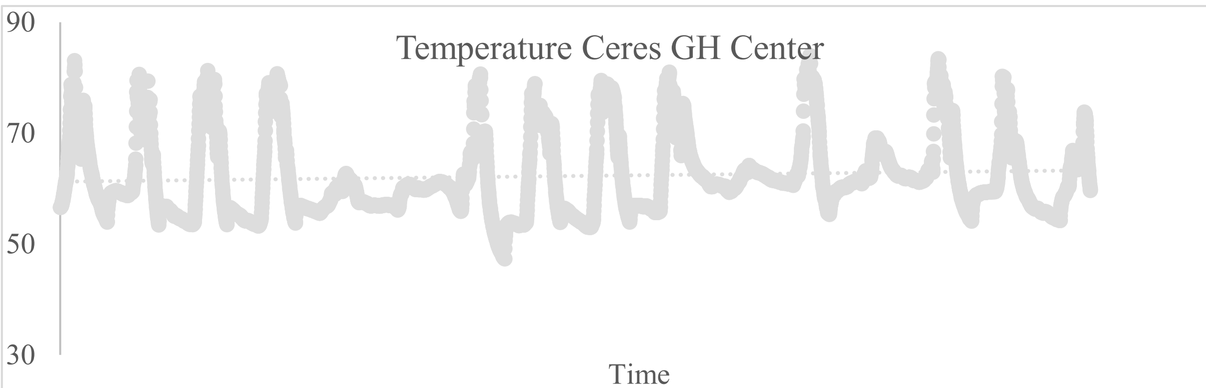
**Question 3 Methods**

To characterize the Coefficient of Performance (COP) of the GAHT, the average energy exchange rate in BTU per minute was given every 5-minutes. The fan was assumed to be running at 1,400 Watts. This converted to 79.613 BTU/min. The COP can be calculated by dividing each 5-minute average energy exchange rate in BTU/min by this BTU/min fan electricity consumption eliminating the units.

When calculating the COP for the intermittently running GAHT when running on auto controls, periods when the fans were running must be identified. For this study a visual inspection of the temperature readings for the greenhouse was conducted to find data segments where the GAHT was running.

Starting with the setpoint and staging temperatures, the inspection identified periods of temperature change that could only have occurred when the GAHT fans were on. This inspection was also based on knowledge of the GAHT controls and temperature setpoints. Figure 14 shows the peaks and troughs that were used in the visual inspection of charge and discharge periods. This estimate of when the GAHT was kicking on or off adds to the uncertainty of the results. In future study there will be current transducers for more accurate timing of GAHT fans running or off, but they were not yet installed for this dataset.

**Figure 14:** *Sample Daily Temperature Fluctuations of the Greenhouse showing visual markers of GAHT on/off periods for visual inspection*




To look at the second part of this question, first a good and bad COP must be defined. For the purposes of this research this limitation is set at 2 for the minimum allowable COP to be considered 'good.' To answer this sub question, temperature drift was established at temperature variation beyond 4°F off of the setpoint.

**Question 4 Methods**

To find the time it takes to establish a relative plateau in the GAHT, first a metric must be established for how this relative plateau can be found. To do this, the discharge was much more obvious. This was also established via visual inspection of temperature data. First, looking at the data from Question 3, the dips where the GAHT kicks on for discharging as well as charging are where the time measurements begin. From there, a visual inspection was continued to see where the estimated plateau begins, looking at where a slope varies from steep to shallow, or the time was measured until the COP falls below 2, whichever occurred first.

If the COP is below 2 this is no longer considered productive energy flow, and begins the plateau process. The visual inspection supported this decision as well. The COP values for GAHT charging can be harder to quantify because the exhaust fans in the greenhouse kick on throughout the day as well, confounding temperature data. On some days and nights, the GAHT fans did not turn on, or did not produce sufficient temperature change due to outside conditions. These time periods were not included.

## Results

This section goes over each of the research questions outlined earlier in this study, and calculates answers to describe and characterize the GAHT. Table 11 shows general surrounding conditions to the GAHT during the month of study. The overall greenhouse maximum and minimum temperatures as well as daily solar radiance are included. Based on these temperature measurements, it can already be approximated when the GAHT controls should be kicking on or off when the fans are running or not.

**Table 14:** *Surrounding Greenhouse Conditions for February*

| Date | Max Temp (°F) | Min Temp (°F) | Solar Radiation (W/m²) | Conditions |
|---|---|---|---|---|
| February 4, 2022 | 68.0 | 58.8 | 42.3 | rain |
| February 5, 2022 | 88.0 | 53.0 | 82.3 | cloudy |
| February 6, 2022 | 89.1 | 53.4 | 94.7 | windy |
| February 7, 2022 | 76.3 | 56.0 | 43.1 | rain |
| February 8, 2022 | 88.8 | 55.7 | 103.0 | cloudy |
| February 9, 2022 | 94.6 | 56.3 | 107.9 | partly cloudy |
| February 10, 2022 | 82.2 | 58.8 | 105.5 | sun |
| February 11, 2022 | 92.1 | 59.1 | 91.0 | partly cloudy |
| February 12, 2022 | 83.1 | 55.7 | 69.6 | rain |
| February 13, 2022 | 80.6 | 54.0 | 78.1 | snow |
| February 14, 2022 | 81.3 | 53.5 | 99.7 | windy |
| February 15, 2022 | 80.7 | 53.3 | 108.3 | sun |
| February 16, 2022 | 62.8 | 53.8 | 17.4 | cloudy |
| February 17, 2022 | 60.8 | 56.2 | 9.3 | rain |
| February 18, 2022 | 80.7 | 56.0 | 71.8 | windy |
| February 19, 2022 | 79.0 | 47.3 | 113.2 | windy |
| February 20, 2022 | 79.5 | 53.0 | 116.1 | sun |
| February 21, 2022 | 81.0 | 54.0 | 96.3 | sun |

| | | | | |
|---|---|---|---|---|
| February 22, 2022 | 65.9 | 59.4 | 8.9 | rain |
| February 23, 2022 | 84.0 | 60.0 | 87.7 | rain |
| February 24, 2022 | 69.1 | 55.3 | 15.9 | rain |
| February 25, 2022 | 83.4 | 61.2 | 108.7 | rain |
| February 26, 2022 | 80.2 | 54.1 | 60.5 | rain |
| February 27, 2022 | 73.8 | 54.3 | 30.2 | rain |
| February 28, 2022 | 59.7 | 54.0 | 1.0 | sun |

**Question 1: Heat Storage Capacity**

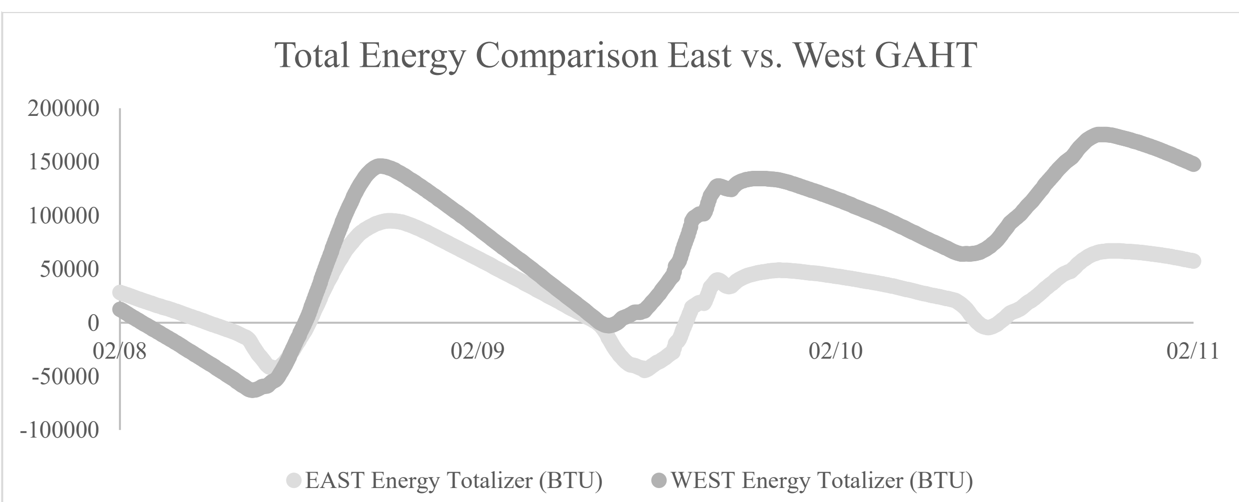
The average of daily total energy transfers for sunny and partly cloudy days with the continuously running GAHT was 11,265,302 BTU for the East and 469,026,369 BTU for the West. This shows a difference from the average for all weather conditions of 8,520,047 BTU for the East and 313,308,466 BTU for the West. The sunny and partly cloudy BTU measurement standard deviation goes to approximately 5,706,329 for the East and 49,418,031 for the West. The average difference between the 5-minute minimum and maximum energy transfers in the whole GAHT system on the conditional days was 200,722 BTU total, meaning that this is the average daily heat storage capacity of the GAHT for heating. Table 12 shows the daily maximum, minimum, and total BTU of the GAHT for both the East and West systems alongside the daily conditions.

**Table 15:** *Energy Comparison for East and West GAHT alongside daily conditions*

| Day | East Sample Max (BTU) | East Sample Min (BTU) | East Daily Total BTU | West Sample Max (BTU) | West Sample Min (BTU) | West Daily Total BTU | Conditions |
|---|---|---|---|---|---|---|---|
| 4-Feb | 24009 | 792 | 2238678 | 286453 | 792 | 285662 | rain |
| 5-Feb | 83180 | -47905 | 6319334 | 734019 | 289760 | 444260 | cloudy |
| 6-Feb | 99045 | -50268 | 9363517 | 985877 | 608785 | 377091 | windy |
| 7-Feb | 56275 | -3910 | 7264751 | 1259316 | 740623 | 518693 | rain |
| 8-Feb | 95091 | -42866 | 9178189 | 1603713 | 1242347 | 361366 | cloudy |
| 9-Feb | 59989 | -44532 | 5722526 | 1570606 | 1313097 | 257508 | partly cloudy |
| 10-Feb | 67023 | -4461 | 10951174 | 1713734 | 1483172 | 230562 | sun |
| 11-Feb | 222782 | 3903 | 17122208 | 1984444 | 1663070 | 321373 | partly cloudy |

There is a performance difference between the East and West GAHT systems. The West stores more energy than the East when looking at daily averages, but this may be because it heats up right around the tube and then cannot extract as much energy at night. Figure 15 shows the daily performance difference clearly. The limited discharge suggests that the indicated storage may be false because it is not actually going very far into the mass of the soil. This means there is not much heat to extract. It heats the tubes up to a higher temperature, but that does not go into the soil. This could potentially be due to installation or compaction issues, or difference in soil, vegetation, or use of the greenhouse. There are also more wye connections and sensors in the below ground system of the East GAHT as well as more human activity and door usage on this side of the greenhouse which could introduce human error. It could also be a result of a systematic sensor error. When looking at the inlet and outlet temperature values, there appears to be a clear performance difference from the West to East of the greenhouse which confirms this energy discrepancy.

**Figure 15:** *Sample Visual Comparison of Total GAHT Energy in the East of the Greenhouse versus the West*



**Question 2: Latent Heat Exchange**

The overall average ratio of difference in inlet to outlet enthalpy and sensible inlet to outlet heat exchange is 2.19 from February 11 to February 28, 2022. In looking at this ratio, the difference in sensible versus adding latent enthalpy can be separated into percentages. In the overall dataset for February 11-28 when the GAHT was running under its control conditions, 97.6% of the 5-minute measurement points had more than a 10% difference between sensible and total enthalpy ratio. In this same set, 94.9% of the points were outside of the 20% difference margin. As can be seen in the table below even the full daily average ratio of sensible heat to enthalpy on partially cloudy, rainy, and windy days still remains over 0.5 which is high. The ratio deviates from 1 quite a bit. This means that the total heat exchange has a strong latent effect. The latent effect could make the ratio higher if moisture is being added. It could make the ratio less than 1 if certain combinations of sensible and latent exchange occur. This shows definitively that humidity makes a difference in the values. It is important to measure latent heat exchange for better performance data of the GAHT. Table 13 shows the daily average ratios of sensible heat to enthalpy for the continuously running GAHT timeline alongside the weather conditions during this period.

**Table 16:** *Daily Average Ratio of Sensible Heat Flow to Total Enthalpy Heat Exchange*

| Date | Daily Avg Ratio | Conditions |
|---|---|---|
| 11-Feb | 1.45 | partly cloudy |
| 12-Feb | 1.88 | rain |
| 13-Feb | 2.04 | snow |
| 14-Feb | 1.71 | windy |
| 15-Feb | 0.29 | sun |
| 16-Feb | 1.61 | cloudy |
| 17-Feb | -0.09 | rain |
| 18-Feb | 1.55 | windy |
| 19-Feb | 1.21 | windy |
| 20-Feb | 1.69 | sun |

| | | |
|---|---|---|
| 21-Feb | 1.37 | sun |
| 22-Feb | 6.00 | rain |
| 23-Feb | 8.05 | rain |
| 24-Feb | 2.73 | rain |
| 25-Feb | 4.64 | rain |
| 26-Feb | 0.50 | rain |
| 27-Feb | 1.50 | rain |
| 28-Feb | 1.38 | sun |

**Question 3: Coefficients of Performance**

The total COP for the continuously running GAHT is 2.4. The total COP for the intermittently running GAHT when the fan was on is 3.8. The average COP for charge for these time periods was 3.6, and the average COP for discharge for these time periods was 2.6.

There is always a difference between the East and West GAHTs favoring the performance of the West side. For the total dataset, when the temperature difference from inlet to outlet is greater than 1 degree, the COP is over 2.0 on average. This suggests that the GAHT should not be running if temperature change is less than 1 degree. Table 17 shows the discharge and charge periods established through this inspection.

**Table 17:** *Charge & Discharge Periods established by visual inspection*

| Day | Discharge Start | Discharge End | Charge Start | Charge End |
|---|---|---|---|---|
| 13-Feb | 2/13/22 12:40 AM | 2/13/22 2:20 AM | 2/13/22 12:50 PM | 2/13/22 3:55 PM |
| 14-Feb | 2/13/22 7:10 PM | 2/13/22 10:30 PM | 2/14/22 11:15 AM | 2/14/22 5:15 PM |
| 15-Feb | 2/14/22 7:40 PM | 2/14/22 11:00 PM | 2/15/22 11:10 AM | 2/15/22 3:50 PM |
| 16-Feb | 2/15/22 8:25 PM | 2/15/22 10:45 PM | | |
| 19-Feb | 2/19/22 12:10 AM | 2/19/22 2:50 AM | 2/19/22 10:10 AM | 2/19/22 5:20 PM |
| 20-Feb | 2/19/22 8:15 PM | 2/19/22 11:30 PM | 2/20/22 10:05 AM | 2/20/22 4:00 PM |
| 21-Feb | 2/20/22 9:15 PM | 2/20/22 10:40 PM | 2/21/22 10:10 AM | 2/21/22 4:35 PM |
| 23-Feb | | | 2/23/22 11:50 AM | 2/23/22 4:20 PM |
| 24-Feb | 2/23/22 9:05 PM | 2/23/22 11:55 PM | | |
| 25-Feb | | | 2/25/22 10:45 AM | 2/25/22 5:30 PM |
| 26-Feb | 2/26/22 12:15 AM | 2/26/22 2:35 AM | 2/26/22 12:30 PM | 2/26/22 4:15 PM |

**Question 4: Energy Plateau**

Based on the data from the continuously running GAHT the daily maximum discharge COP was normally reached between midnight and 8:30AM. This is a large window which the study does not explain, but did show how the discharge period can extend. The daily maximum charged COP was normally reached around noon or in the early afternoon. Based on the values provided by visual inspection, the average time from the GAHT turning on to discharge to a soil temperature plateau is approximately 2.5 hours. Based on this quantification and overall analysis of daily GAHT behavior, the system should probably not run for longer than 3 hours at a time for peak performance.

## Conclusions and Future Research

The following section covers a summary of the outcomes in this study and a variety of future experiments which could result from this baseline characterization and instrumentation. This work established the sensors and data collection methods to do further analysis of this GAHT installation, and provides the groundwork for further characterization in cooling conditions as well as a side-by-side GAHT comparison of the two systems within the greenhouse. Differences need to be better understood for the East and West GAHT systems.

For this study, it could be clearly established that latent heat is important in GAHT characterization. A basic outline of daily heat storage capacity could be framed at 4500 BTU to be compared with future heating seasons.

Overall, the operational goal of the GAHT is to make a bigger temperature difference between inlet to outlet, and soil to greenhouse temperature, for greater efficiency. Based on this goal and the data of this study, the GAHT could be run for periods shorter than 3 hours to save energy.

It would be interesting to know whether the whole system could run on just one of the fans or a weaker fan for improved energy efficiency. It may also be less energy intensive when looking at cooling. The cooling of the GAHT should be a focus of future research as well, as it is already entering cooling mode in the heating season, so summers should produce interesting data. More comparison should be done of looking at ‘charging’ of the GAHT versus cooling, since the exhaust fans can potentially do a lot of the cooling work using less energy until outside temperatures reach high enough points that a lower soil temperature may be more useful.

There should also be a re-sampling of soil within the GAHT for soil texture as well as conductivity readings with more breadth. Additional ideas for next steps include studying the entire heating season beyond just February, adding current transducing sensors to know exactly when the GAHT fans are on or off, adding soil sensor readings, looking at underground GAHT temperatures and relative humidity changes, as well as looking at the GAHT fan control strategies with the Delta between inlet and outlet. It could also be interesting when looking at the energy balance to consider soil moisture around the GAHT, and how this affects heat storage, especially when the water drains out from under the foundation.

This Ceres high efficiency greenhouse can serve for future greenhouse study side-by-side with the neighboring hoop house. In terms of subsequent work, establishing a way in which to calculate the COP of the GAHT as done in this paper can assist in future studies. Having time ranges to compare for the charged plateau of the GAHT both for future heating seasons as well as when then earth battery is used in cooling will serve subsequent research as well. Some continued experimentation can be done to see the longevity of a charge, and whether heat from the ground can be maintained and used for the greenhouse for an extended period.

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## Vita

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