To the University of Wyoming

The members of the Committee approve the thesis of Yara Thomas presented on August 26.

Liping Wang, Chairperson

Urszula Norton, External Department Member

Anthony Denzer

APPROVED:

(Thomas, Yara, Sustainable Greenhouse Design) MS, Architectural Engineering and Environment
Natural Resources,

Fall, 2017

SUSTAINABLE GREENHOUSE DESIGN AND MODELING

By

Yara Thomas

A thesis submitted to the MS Program, Civil and Architectural Engineering Program

and the University of Wyoming

in partial fulfillment of the requirements

for the degree of

MS

in

ARCHITECTURAL ENGINEERING & ENVIRONMENT NATURAL RESOURCES

Laramie, Wyoming

August 2017

COPYRIGHT PAGE

Executive Summary

Controlled Environment Agriculture (CEA) — food production in greenhouses — is recognized to be an important strategy for meeting the growing food demand in the U.S. and worldwide. The controlled environment of a greenhouse allows for production of crops in a variety of climates worldwide and year round. Unfortunately, conventional greenhouses consume more fossil fuel energy in the operation of mechanical systems than other similar sized buildings, and therefore have larger carbon footprints. Greenhouse operation is challenging because the crops require control of CO_2, and moisture as well as temperature and because light-weighted construction makes the greenhouse environment susceptible to climate and outdoor weather conditions. These challenges brand greenhouses as one of the most energy intensive sectors of the agricultural industry, and thus, have become a great area of focus for energy efficiency research. Thoughtful design and energy efficiency strategies for greenhouses can help to mitigate large energy requirements.

This Report presents research on CEA beginning with a discussion of CEA as compared to open-field agriculture and a literature review of environmental control technology in agricultural greenhouses. This is used to inform and direct research on simulation of the greenhouse environment and the use of EnergyPlus, a building simulation software, to accurately represent the greenhouse environment. Finally, a specific case study is examined in which EnergyPlus is used to gage the potential of waste heat utilization for greenhouse heating. This research identifies areas in which future research has the potential to reduce greenhouse energy consumption and improve control operation in order to employ greenhouse food production as a major component of the agriculture industry.

Outline of Review

Figures

Tables

Chapter 1 Introduction

Controlled Environment Agriculture (CEA) or the production of food in a space independent of external climate and weather conditions [1], is recognized to be an important strategy for meeting the growing food demand in the U.S. and worldwide. The controlled environment of a greenhouse allows for production of crops in a variety of climates worldwide and year round. Unfortunately, conventional greenhouses consume more fossil fuel energy in the operation of mechanical systems than other similar sized buildings, and therefore have larger carbon footprints. Greenhouse operation is challenging because the crops require control of CO_2, and moisture as well as temperature and because light-weighted construction makes the greenhouse environment susceptible to climate and outdoor weather conditions. While these challenges make greenhouses one of the most energy intensive sectors of the agricultural industry, there are also many advantages to CEA. Advantages include decreases in land, water and pesticide use along with increased yield. Thus, greenhouses have become a great area of focus for energy efficiency research. Thoughtful design and energy efficiency strategies for greenhouses can help to mitigate large energy requirements.

It is important for research to examine specific engineering and cultural practices to reduce energy consumption but, it is also practical to gage the sustainability of CEA in relation to the whole agricultural industry. Only by taking a broad view of the system can research identify areas in which research can have the largest environmental benefit. It is important to recognize that CEA will never fully replace open field agriculture because there are many crops in many climates that grow very efficiently outdoors. The future of CEA is not in attempting to replace these systems but rather identifying under what circumstance open field agriculture is inefficient and attempting to fill those gaps with local, sustainable markets.

This research begins by briefly comparing open field to CEA agriculture and identifying some of the challenges associated with this process. It identifies sustainable energy operations and the incorporation of renewable resources for greenhouse climate control as a tipping point that can make CEA feasible as an alternative to open field production. A literature review examines existing technologies that have been applied to this field and determines the need for a modeling tool that can accurately represent the greenhouse environment. These two concepts, the need for an advanced modeling tool and incorporation of energy efficiency strategies and renewables, are then considered through original research.

The first component of original research is to compare the results from an EnergyPlus simulation of an existing greenhouse on the University of Wyoming campus, to measurements gathered from the actual space. EnergyPlus is an algorithm based software that allows the user to construct a building virtually and calculate loads. Thousands of inputs are considered including building geometry, materials and construction, mechanical systems, set point temperatures, and climate data. From this the energy requirements for the building can be predicted over any time interval. This validation model attempts to simulate the advanced nature of a greenhouse by utilizing several features of EnergyPlus. It is determined that to accurately represent the full complexity of the greenhouse environment, much more experimentation and a more in-depth understanding of the EnergyPlus features are needed. However, the simulation was effective in predicting energy consumption and zone temperatures. These two attainable aspects of simulation are applied in the second study.

EnergyPlus modeling is applied to determine the feasibility of a greenhouse heated by waste heat in Lovell WY. Waste heat is defined as "heat that is either lost through the flue stack of an industrial operation, or which is rejected from a power generation station to improve the thermodynamic efficiency of the cycle" [2]. There is a great potential to save money and natural resources by harvesting this heat for use in smaller facilities. Electrical energy consumption of a three acres greenhouse heated with a traditional, electric variable air volume system, is compared to two systems which use waste heat.

This study is not only instructional and demonstrates the great potential in waste heat utilization for greenhouse heating, it encourages simulation to advance the field of greenhouse design. Many of the studies regarding greenhouse HVAC design took place before the development of sophisticated modeling tools such as EnergyPlus. As a result, research lacks a common standard by which to share and build information. Reducing energy consumption is a key component to building sustainable agricultural system along with understanding the benefits of controlled environment in agricultural application, its limitations and its strengths.

Chapter 2 Literature Review

Controlled environment agriculture utilizes technology to enhance the environment in which crops are grown. Technology can vary from simple hoop houses or screen covers to very advanced automated systems that regulate all aspects of the environment including temperature, humidity, CO_2 concentration and light. The goal of controlled environment agriculture (CEA) is to increase the yield or health of the plants and thus make the systems more efficient. However, there are inputs associated with controlling the environment. These inputs include additional materials, construction, energy of operation such as heating and cooling, and continued maintenance. The energy consumption and environmental impact of these inputs can be significant however, there are also many benefits associated with CEA. The controlled environment allows crops to be grown closer to urban centers and locations of consumption. CEA often increases yield, decreases water consumption, and reduces the need for pesticides. On top of this, the demand for local food is growing rapidly. These advantages are significant however, it is less obvious if these systems are truly more sustainable then open field agriculture. It is difficult to compare the sustainability of the two agricultural systems because they contain many different variables.

The controlled environment of a greenhouse allows for production of crops in climates and season which would otherwise prohibit growth. This allows for crops to be grown closer to urban centers and locations of consumption. CEA often increases yield, decreases water consumption, and reduces the need for pesticides. On top of this, the demand for local food is growing rapidly. These advantages are significant but, maintaining the environmental conditions necessary for plant growth involves regulation of temperature, humidity, light availability and water use. Thus, greenhouses are one of the most energy and water intensive sectors in the agricultural industry. Reducing high energy and water demand within agricultural greenhouses, while increasing crop yield, becomes a key industry sustainable development goal [3].

This literature review focuses on research related to greenhouse environmental control. It briefly discusses architectural and material innovations in the greenhouse industry. The literature review emphasizes different types of heating and cooling technology applied to greenhouses as well as the integration of renewable resources. The review also covers energy saving measures in the form of control strategies and their associated sensing and monitoring technology and algorithmic control. Finally, it discusses available simulation software for greenhouses. The goal of this review is to determine areas in which research needs to be further conducted and in which there is a potential to cut down on greenhouse gas emissions through reducing agricultural greenhouse energy consumption.

2.0) Food Security and Controlled Environment Agriculture

Food security is one argument for controlled environment agriculture. Here we discuss some of the major contributing factors towards food insecurity and the growing gap between the demand for food and the availability of arable land. Many of these factors are exaggerated by the effects of climate change but, it is unclear what the overall effects of global warming will be on our agricultural systems. Many models suggest that a slightly warmer climate and higher concentrations of CO2 in the atmosphere will benefit agriculture in the US. On the other hand, these models often do not account for severe weather scenarios or pests and disease. Due to the unpredictable nature of the climate we are facing uncertainty and thus insecurity in our agricultural systems. Controlled environment agriculture provides security by eliminating uncertainty.

Food security means that all people in a population have access to sufficient food to lead healthy and productive lives. There are three primary components to this [4]: availability, access, and utilization meaning respectively that there is sufficient food for everyone, each person or household has adequate income and recourses to obtain food, and that each person is able to eat and absorb nutrients from food. Food security is an incredibly complex issue because of the its multifaceted nature. It is based not only on the ability of the land and climate to support crops but also on trade, political atmosphere, disease, pests, and even culture. The complexity of this issue is compound by uncertainty associated with global warming and climate change.

The world population is expected to grow from 7 billion in 2011 to 9.2 billion in 2050 [5]. In order to sustain the growing population, we need to produce more food, however, there are many factors that limit our ability to meet this need. Some of these factors include soil quality degradation, limited availability of water, climate change, competition for land, and cultural preference.

The first of these, soil degradation, can be due to erosion, salinization, organic matter and nutrient depletion, and elemental imbalance. These are all common occurrences that can result in decreased yield or render land un-farmable. Soil degradation is often a result of poor farming practices which extract nutrients from the soil without sufficient time or crop rotation to replenish it.

Population growth and urbanization lead to competition over agricultural land. As cities expand outward, agriculture is pushed further from city centers. This necessitates the conversion of natural landscapes into agricultural fields and lengths the time from harvest to consumption. Vast quantities of food are wasted before they leave the market. It is estimated that up to 30 percent of all produce is lost in transportation and distribution. Furthermore, rich top soil top soil is also used for brick making, production of biofuel, and other non-agricultural uses.

Another major cause of food insecurity is the trend towards animal over a plant based diet [5]. Studies indicate that the production of one kilogram of beef requires 104 times the square area of land compared to one kilogram of potatoes [6]. A similar study concluded that the energy intensity of beef production is 40 MJ/kg while it is 1.8 MJ/kg for potatoes. To raise livestock, a large portion of land is dedicated to growing feed rather than for direct human consumption. As much as 35 percent of cereal crops are for animal feed [7]

Decreased availability of water is due to over use and to climate change. Aquifers are being depleted and rain is less consistent and predictable. In many cases, intense drought is followed by heavy rains with lead to excessive erosion, flooding and further destruction of crops. Global warming directly influences precipitation. A hotter environment leads to greater evaporation which increases the intensity and duration of drought. On the other hand, each 1°C warming, increases the water retention capacity of air by about 7% [8]. Thus, storms of all kinds tend to be produce more accumulation and the risk of flooding and related damage is increased

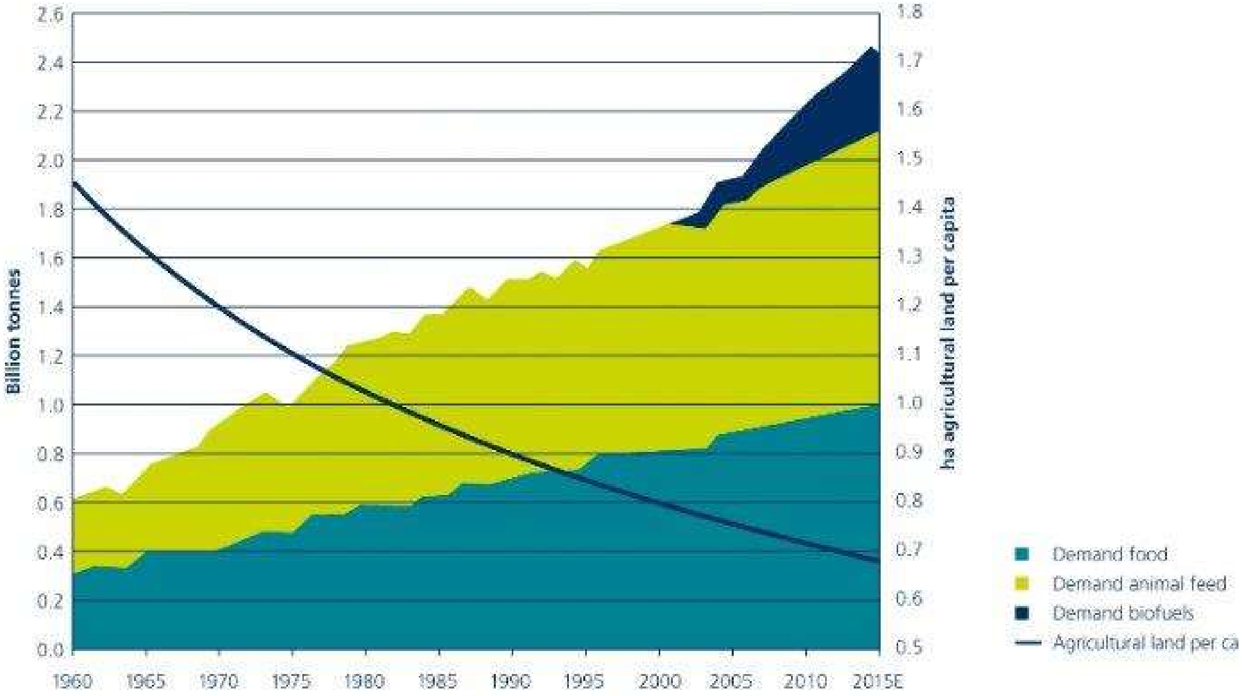


Figure 1: Agricultural demand vs. land per capita [9]

These factors have resulted in a large gap between agricultural demand and the amount of arable land per capita as shown in figure 1. One practical solution to this issue is to increase yield on current agricultural land. Increasing yield means that more food is produced per area of land. There are many ways to achieve this but it is extremely difficult without using excessive amounts of fertilizers and pesticides. Farmers must have specific knowledge of the microclimate, soil and crops where they are growing. They must practice crop rotation, carefully select seeds, and balance the chemical balance of their fields. There is no blanket equation for successfully managing all components. Best practices may vary even between neighboring fields based on the history of the land. Because of this, it takes farmers many years and sometimes generations to maximize yield. Even once best practices for a piece of land have been determined, a low water year or hot spring can reduce yield.

Because farming is such a subtle art, climate change is likely to decrease yield unless we can accurately and quickly adjust to the changes. Undoubtedly some areas of the country will become more difficult to farm while others will improve. Modeling is one way that science has attempted to predict the future of agriculture. Typically, these models consider variables such as temperature, accumulation or rainfall, carbon content of the air and length of the growing season. Although there are many other factors that influence our agricultural systems, these contribute directly to plant growth. Results from models measuring yield have often been combined with models of potential markets or economic models to gage the future of the agricultural industry.

Early economic assessments of the effects of climate change on agriculture include those by [10–15] Results from these studies suggest that climate change is not a food security issue for the U.S. although reductions in crop yields are shown to have economic consequences for some regions of the U.S [16]. These results are, in part, due to increased yield in an atmosphere with higher levels of carbon dioxide and longer growing season in northern climates.

In a more recent study, Reilly et al, 2003, considered impacts on crops, grazing and pasture, livestock, pesticide use, irrigation water supply and demand, and the sensitivity to international trade assumptions. Findings suggest that the aggregate of these effects were positive for the U.S. consumer but negative, due to declining crop prices, for producers [17]. Similarity, Tubiello et al., 2002, looked at 45 representative sites, using 2 scenarios of climate change, developed with the Hadley Centre Model and the Canadian Centre Climate Model, and the DSSAT (Decision Support Systems for Agro-technology Transfer) dynamic crop-growth models. These simulation results were aggregated nationally with the aid of economic models to show an increase in overall US agricultural output under climate change [18].

Other models, which attempt to predict future scenarios for agriculture, focus largely on Europe with only a few in Asia and other continents. [19] modeled future scenarios of European agricultural land and estimated changes in crop productivity. [20] modeled climate impacts on European agriculture and water management in the context of adaptation and mitigation. [21] looked at impacts of present and future climate variability on agriculture and forestry in the temperate regions of Europe, [22] looked at consequences of climate change for European agricultural productivity, land use and policy and [23] investigated uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. Finally [24] assessed the risk of drought by modelling impacts of climate change on wheat yields in England and Wales. Other studies include those by [25] and [26].

While results from these models vary, all suggest that it is difficult to predict the overall effects of climate change on agriculture. Over the past thirty years, research in the form of modeling has developed rapidly, however, challenges associates with such a complex issue still exist. The validity of models depends on many layers of simulation. Even the most basic climatic prediction of future mean temperatures is highly contested. More complex models which attempted to predicted precipitation or microclimates are unreliable and in many cases, contradict each other. Because agriculture is so closely tied to temperature and precipitation, regional distribution of the simulated crop yields largely depends on the precipitation projected by the climate scenarios [18]. The variability of these models means that there is an even larger degree of uncertainty associated with agricultural models.

While the models can be expected to be accurate to some degree when it comes to direct impacts of climate change on agriculture, models fail to account for climate variability and extreme weather. These factors such as extreme temperature, drought, heavy rainfall and flooding, tropical storms and pests and diseases may play a large role in food security and the future of agriculture.

Controlled environment agriculture, growing within a controlled environment such as a greenhouse or warehouse with grow lights, can increase yield and eliminate many of the variables that make open field farming so unpredictable. These systems operate independently from outdoor conditions though heating, cooling, controlled ventilation, lighting and in some cases CO2 enrichment. Each aspect of the greenhouse environment can be regulated to optimize growth of the plants. Unfortunately, this is a much more energy intensive process. As such, direct energy consumption of the facility must be outweighed by indirect energy savings.

Besides eliminating the uncertainty associated with the outdoor environment, controlled environment agriculture offers food security by increasing yield, reducing the environmental foot print, and allowing food to be grown close to urban centers. One innovative agriculture tech company, Plenty, claims to get 350 times the crop yield per year over an outdoor field farm. Or, as Barnard, CEO and cofounder described, “It is the most efficient in terms of the amount of productive capacity per dollar spent, period.” [27]. These facilities can be located within an hour of hundreds of supermarkets and centers of distribution. This cuts down on loss of produce, transportation energy and maintains nutritional quality.

Plenty is not the first company to attempt to localize and condense agricultural systems. A recent trend has seen many of these companies spring up all over the world. Unfortunately, it is not an easy market to crack. Produce is cheap and it is difficult to find the balance between maintaining these high-tech facilities and making a profit. Many companies have failed after only a few short years. However, the continued demand for local food and the need for a less land intensive system suggests that controlled environment agriculture will play a role in the future of agriculture.

2.1 Energy Intensity of Agricultural Systems

To assess the environmental impact of controlled environmental agriculture compared to open field agriculture, research is examined which attempts to quantitatively compare these systems. Two methods that have been applied to this challenge are summarized. Results from these two methods, life cycle analysis (LCA) and input-output analysis, are compared. These two methods were chosen because they allow the inclusion of many variables such as water consumption and pesticide use as well as direct energy use. The primary difference between these two methods is the definition of boundaries. While input-output examines direct inputs to the agricultural system (such as water for irrigation, heating and cooling energy exc.), LCA considers the system from allocation of natural resources all the way to consumption or disposal. This provides a view of the bigger picture rather than agriculture as an isolated system.

Many tools have been developed which attempt to take into consideration the full sophistication of the the phenomenon. They all have advantages and disadvantages. Several tools have been used. These include: Athena Impact Estimator for Buildings, CMCLA, COMPASS, eVerdEE , GaBi 4.4, Emissions Model for Integrated Systems (GEMIS), openLCA, 2.3 – Corporate Eco performance Software, Savvy Pack®, Sustainable Minds®, Umberto and Life Cycle Assessment Tool Input Form are all tool that perform LCA.

When comparing the results obtained through these tools it is important to define a metric or standardized unit. Based on the most common units found in the literature, energy use efficiency, also called output energy to input energy ratios, is used. This metric assumes yield (amount of crop produced per unit area) as the total measure of productivity. It is a calculation of how many units of produce can be grown given a unit of energy. When applicable, water and fertilizer use will also be compared as important indicators of sustainability. Unfortunate, there are many ways to define systems and many variables to consider including climate, research period and methods. Because of this it is challenging to directly compare results. Instead, this review will highlight important results and then qualitatively discuss the implications and make inferences.

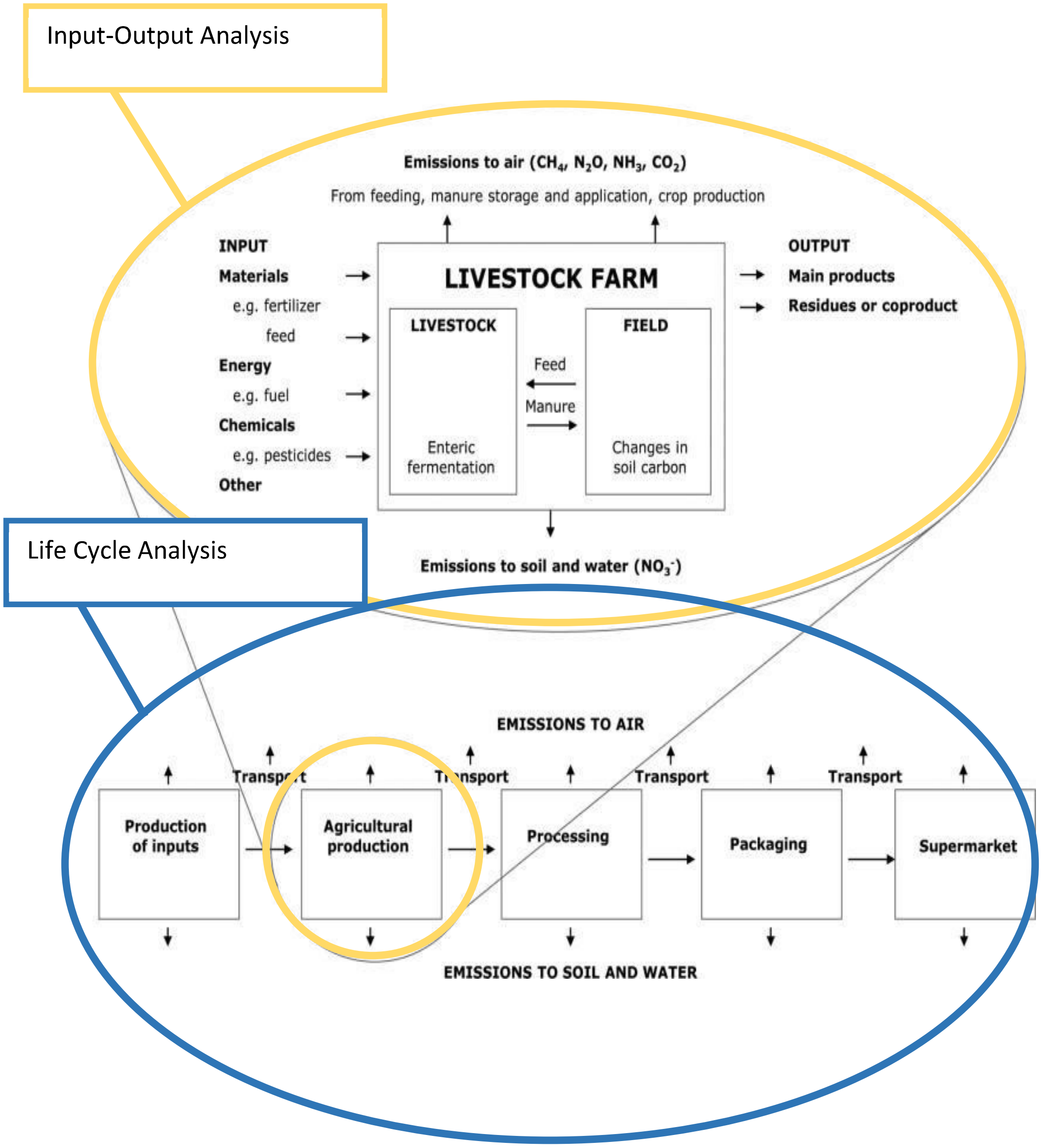


Figure 2: Diagram Demonstrating the Relationship between Input-Output and Life Cycle Analysis

Life cycle analysis or life cycle assessment is an increasingly important tool for gaging sustainability within industry and for environmental policy. This method is unique because it considers more than the direct inputs of a process or product. It allows the user to define system boundaries that include many variables and their associated inputs. To choose the most sustainable product or policy it is necessary to consider its environmental impact from “cradle to grave”. This includes the future fate of the product as well as indirect inputs to the production process and associated wastes and emissions [28]. Figure 1 shows how the system boundaries are different for LCA and input-output analysis. There are four linked components of LCA [29]. The first task is to define the goal and scope so that system boundaries can be defined. This is a definition of what is and what is not included in the study. The second step is to quantify the energy and raw material inputs and environmental releases associated with each stage of production. These can then be assessed in terms of impact on environment and human health. Finally, opportunities to reduce environmental impact are evaluated.

2.1.1 Input-Output Models

Through input-output analysis Ozkan et al. [30], investigated the energy intensity of greenhouse vegetable production in the Antalya region of Turkey. Energy intensities was calculated by dividing the yield equivalent by the energy input equivalent. This means, how many crops were produced per unit of energy. The ratios for greenhouse tomato, pepper, cucumber and eggplant were estimated to be 1.26, 0.99, 0.76 and 0.61, respectively. This indicates that intense use of inputs was not accompanied by satisfying yield increase. When inputs where averaged between the four plants, diesel fuel was determined to have the largest share of inputs. Nitrogen has the second largest impact while water for irrigation was found to be very insignificant. Results from a previous study in the same area indicate even lower energy output-input ration of 0.32, 0.19, 0.31, 0.23 for tomato, pepper, cucumber and eggplant respectively.

The results of the study by Ozkan et al. [30] demonstrate a higher energy intensity for greenhouse crops then studies on open-field crops using a similar method. Yaldiz et al. [31] performed and input-output analysis for field grown sugar beets, corn, chickpeas, soybeans, sunflowers, barley, wheat, cotton, beans and potatoes and found an average intensity of 3.3. Similarly, Singh [32] looked at mustard crop and wheat in India and found an average intensity of 1.88. These values indicate that the greenhouses, as studied by Ozkan et. al., had a higher environmental impact then similar studies on open field agriculture. However, that a typical European greenhouse yields more than three times the same size greenhouse in Turkey. This is due to more efficient use of inputs, more productive varieties, and better environmental control [30].

A very similar study conducted by Heidari & Omid [33], gathered similar results for tomatoes and cucumber greenhouse production in Iran. Data obtained through face-to-face interview returned energy ratios of .69 and 1.48 for cucumbers and tomatoes respectively. They also found that diesel fuel and fertilizers consumed the most energy (49% and 24% respectively). Additionally, they found that renewable energy made up less than 5% of shares. This creates a great opportunity for renewable resources such as green manure instead of chemical fertilizers and solar energy and natural gas instead of diesel fuel to improve the situation.

Another input output analysis conducted by Yousefi et. al [34] compared greenhouse and open field cucumber production in Iran. Through face-to-face questionnaires of 50 greenhouse farmers and 50 open-field farmers, they found that one acres of greenhouse consumes nearly 150 times the amount of energy that one acres of field consumes. When the yield was considered, open-field cucumber production was found to be 20 times more energy productive.

Table 1: Breakdown of yield, energy, and water use

Production Method	Yield (kg/m^2/y)	Water Use (L/kg/y)	Energy Use (kJ/kg/y)
Conventional	3.9	250	1100
Hydroponics	41	20	90000

Barbosa et. al. [35] compared land, water and energy requirements of hydroponic vs conventionally grown lettuce in Yuma, Arizona. Data regarding open field agriculture was sourced from crop budgets and governmental agriculture statistics while hydroponic lettuce data were derived by using engineering equations populated with literature values. Table 1 shows a breakdown of the results with yield: 3.9, 41; water use: 250, 20; and energy use: 1100, 90000 for conventional and hydroponic respectively. The authors note that although the hydroponic system is much more efficient in terms of yield and water use, energy use is significantly higher. They discuss the fact that cooler climates or areas where renewable energy can be incorporated the energy intensity of hydroponics would be significantly reduced. One major limitation to this study was that the energy intensity of the open field did not account for transportation energy.

2.1.2 Life Cycle Assessment

Life cycle analysis is one of the most effective ways to evaluate how a product will affect the environment. This makes it beneficial in two primary ways [36]. A standardized and reliable way to assess sustainability of a product allows consumers to make informed decisions. In turn, this drives innovation by giving manufacturers and producers incentive to improve the sustainability of their products. LCA also reveals areas in which improvement can be made and helps to target areas of the system that are particularly inefficient. For example, through LCA a cement manufacturer might realize that although he is getting a great price on aggregate from southern New Mexico, the energy associated with shipping it to Washington is 30% of the total energy associate with his product. For a very slight increase in price he can localize his source of aggregate and increase the energy efficiency of his product by 25%.

Although LCA has been evolving for several decades, only more recently has it been applied to the agriculture industry. While few studies cover the life cycle of greenhouse produce, a number of studies have used LCA to examine the environmental impacts of the agricultural industry. These include studies of milk: [37–43], soybeans: [44], vegetable oil crops: [45], grain [46,47], rice: [48–50] wine [51–56], potatoes [57], carrots: [58], and fruit: [59–66]

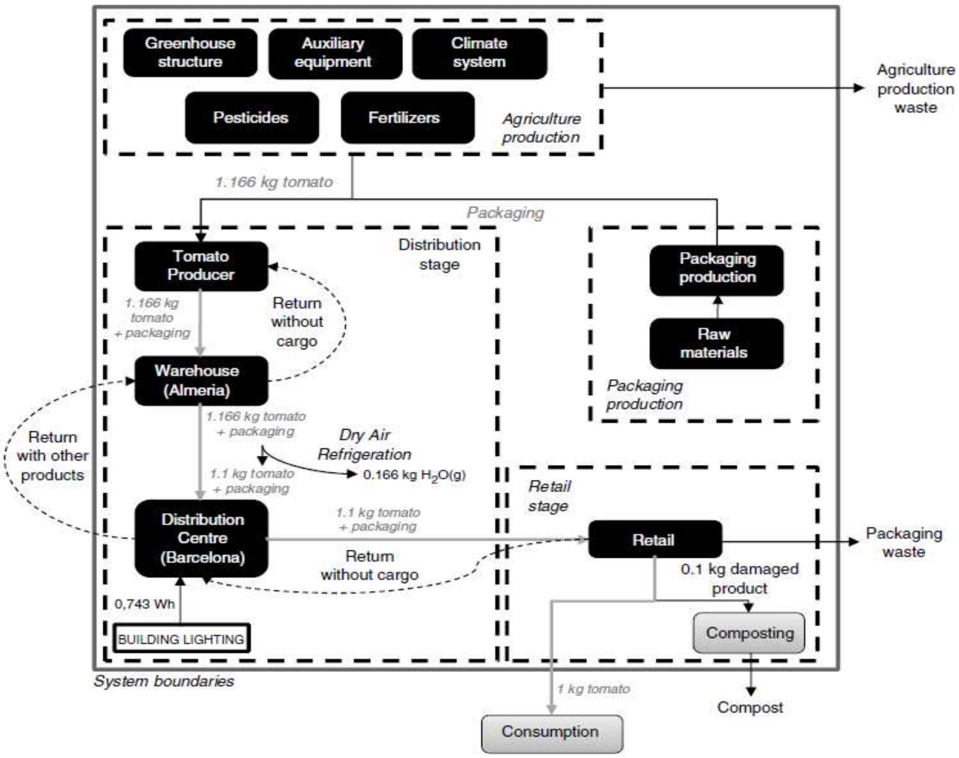


Figure 3: Inputs, outputs, and boundaries of the linear system

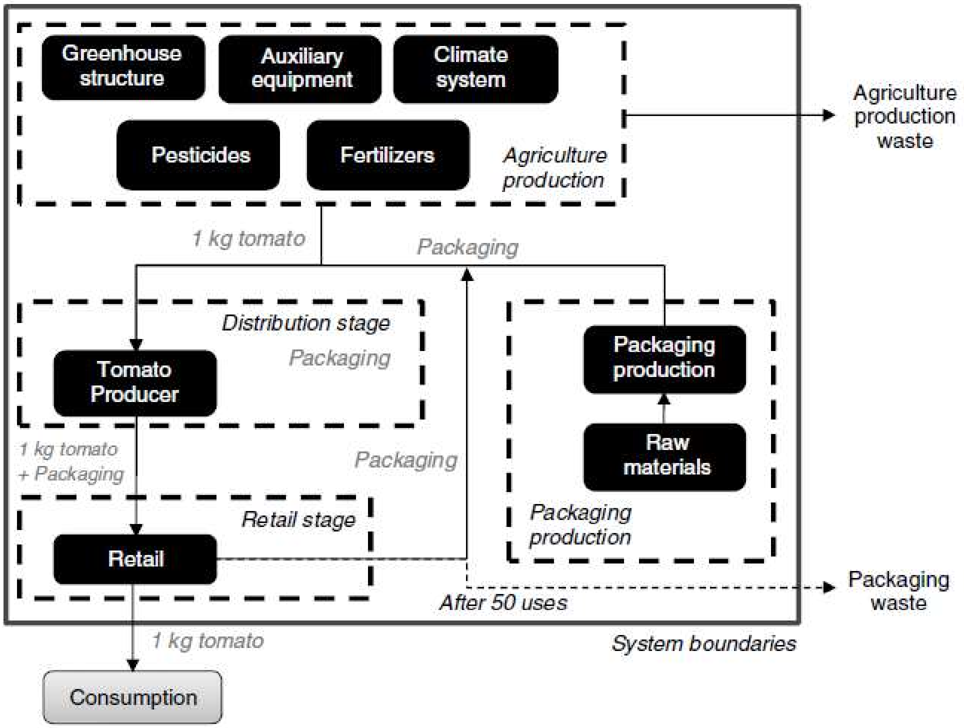


Figure 4: Inputs, outputs, and boundaries of the roof-top greenhouse

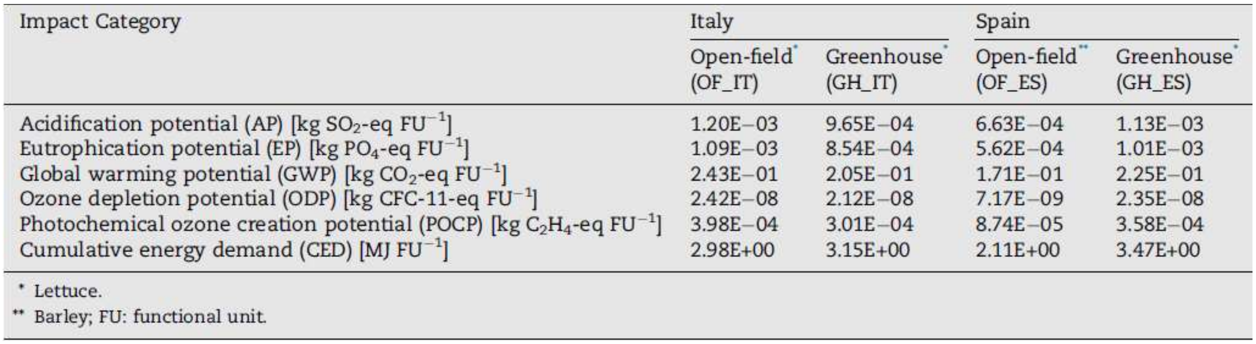
Previous LCA studies have also been used to analyses and evaluate the environmental impacts of greenhouse vs open-field production, and different types of greenhouse structures, coverings and technologies in different countries: soil vs hydroponics, conventional vs organic growing, integrated vs chemical pest management, energy sources, artificial lighting, CO_2 enrichment, growing media, fertirrigation system, recirculation of drain water, and farm size as cited in [67].

Application of life cycle analysis to controlled environment agriculture

One of the best examples of LCA applied to controlled environment agriculture was conducted by Esther Sany´e-Mengual et. al. [68]. This study quantified and compared, through a life cycle assessment, the environmental impact of a current linear produce supply system with a roof-top greenhouse system by using a case study for the production of tomatoes in Barcelona. The linear system is assumed that fresh tomatoes are imported from Almeria and locally distributed from MercaBarna, which is a food distribution center situated in the same general region of Barcelona. Figures 2 and 3 show the inputs, outputs, and boundaries of the roof-top greenhouse and linear system respectively. Results indicate that the roof-top system could reduce the different impact categories in the range of 44.4–75.5% per kilogram of tomatoes. This would also result in up to 73.5% in energy reductions. These savings are associated with re-utilization of packaging systems (55.4–85.2%), minimization of transport requirements (7.6–15.6%) and reduction of the loss of product during transportation and retail stages (7.3–37%).

Bartzas et. al, [69] a life cycle assessment (LCA) study regarding barley and lettuce production in the Barrax and Santomera regions of Spain and the Albenga region of Italy. LCA was conducted for both open field and standard greenhouse cultivations in order to evaluate energy consumption and environmental impacts. The analysis was performed through the GaBi 6 software package and specific related databases and system boundaries included agricultural machinery manufacture, nursery production, and waste management and raw materials transportation. Figure 4 shows a summary of the impact category results for each system in each location. These impact categories are typical for a LCA applied to agricultural systems. Most notably, the results for open-field agriculture are very different in the two locations while the greenhouses in both locations have similar impacts. In Italy, except for the cumulative energy demand, greenhouse production has a lower impact in all categories. In contrast, greenhouse production in Spain is more intensive then open-field in all categories except ozone depletion potential.

Table 2: Summary of impact category results for each system in each location



Impact Category	Italy		Spain	
	Open-field* (OF_IT)	Greenhouse* (GH_IT)	Open-field** (OF_ES)	Greenhouse* (GH_ES)
Acidification potential (AP) [kg SO_2-eq FU^{-1}]	1.20E−03	9.65E−04	6.63E−04	1.13E−03
Eutrophication potential (EP) [kg PO_4-eq FU^{-1}]	1.09E−03	8.54E−04	5.62E−04	1.01E−03
Global warming potential (GWP) [kg CO_2-eq FU^{-1}]	2.43E−01	2.05E−01	1.71E−01	2.25E−01
Ozone depletion potential (ODP) [kg CFC-11-eq FU^{-1}]	2.42E−08	2.12E−08	7.17E−09	2.35E−08
Photochemical ozone creation potential (POCP) [kg C_2H_4-eq FU^{-1}]	3.98E−04	3.01E−04	8.74E−05	3.58E−04
Cumulative energy demand (CED) [MJ FU^{-1}]	2.98E+00	3.15E+00	2.11E+00	3.47E+00

* Lettuce.

** Barley; FU: functional unit.

Muñoz et. al. [70] use a Life cycle assessment tool to compare the environmental impacts associated with greenhouse as opposed to open-field production processes for a spring season tomato crop grown in the Maresme region near Barcelona. Subsystems including greenhouse structure, irrigation equipment, fertilizers, pesticides, cultural tasks and irrigation were analyzed. The inputs for each subsystem were traced back to primary resources and categorized based on impact. They found that environmental impact per kg of tomato grown in open-field production was greater than that for tomatoes produced in greenhouses with respect to factors such as the use of water, fertilizers and pesticides. This combined with the high demand for greenhouse and local produce resulting in high economic returns makes greenhouse production feasible.

Martine Dorais with Biosystems Engineering, IRTA in Barcelona, Spain collaborated with Doctors Anton and Montero of Lavel University, Quebec to conduct a life cycle analysis of new sustainable greenhouse growing systems. They found that high energy demand had the major contributions to all impact categories when fossil energy is used. Biomass offered an efficient alternative and reducing the distance from the farm to the biomass source reduced environmental impact related to energy. Greenhouse structure made the second highest contributions to environmental impact categories [67].

2.1.3 Controlled Environment Agriculture with Integration of Renewable Energies

Dorais et al. went on to test their theory that incorporation of biofuels would increase sustainability and thus feasibility of organic greenhouse. In one study, they compared an organic tomato growing system which used wood biomass as a heating energy and artificial wetland to treat affluent to an open conventional tomato growing system which used fossil fuel as heating energy. Both scenarios had the same construction, location, irrigation systems, and environmental controls other than heating systems. When wood biomass was incorporated the CO_2 footprint of 1 kg of tomatoes was 0.812 kg CO_2 eq kg-1, while the impact of an open conventional growing system using fossil energy was 5.788 kg CO_2 eq kg-1. Additionally, assessment of the fertilizer in the closed-loop organic crop had 12 times less environmental burden on abiotic depletion and 6 times less acidification. The closed loop system also decreased eutrophication by 136 times and global warming by 10 times compared to the open conventional growing system [71].

One life cycle assessment study calculated that tomatoes grown in a greenhouse heated by bio-fuel were found to be better in all studied life cycle impact categories compared to a field-grown tomato transported over a long distance. However, a scenario in with fossil energy was used to heat the greenhouse had a higher impact compared to the long distance transported tomatoes in most categories studied [72]. This indicated the importance of efficiency strategies and a shift towards more renewable energy systems.

Perspective

These two types of analysis make it clear that sustainability of agricultural systems is relative to perspective. When considered as isolated units, open field farms were far less energy intensive per unit of food produced, however, once transportation and other aspects such as water consumption and the effects of fertilizer leach into the environment are considered, greenhouse start to look like a much better alternative. This is an important and vastly complicated concept to consider. Innovation and energy efficient design of greenhouse can help to reduce the foot print of the entire industry.

2.2 Classification of Greenhouses

Greenhouses can be classified by several criteria including construction, glazing, covering, and number of spans. However, the most common and useful classification is based on greenhouse technology. Three categories have been defined to help determine the most appropriate design based on need and budget. These are high, medium, and low technology greenhouses. The categories are used often because greenhouses are technology based investments and are more likely to achieve a controlled growing environment with a higher level of technology [73].

A low technology or low cost greenhouse has little control over ventilation and the greenhouse environment. The structure is generally less than 3 meters tall with curved walls such as a tunnel house. They are more prone to pests and to the spread of disease. Generally, low tech greenhouses have a limited yield due to a suboptimal environment, however, the low initial and operational costs can make these greenhouses cost effective.

A medium technology greenhouse is generally more spacious and has a higher roof than low tech greenhouses. Structures are typically clad in single or double skin plastic or glass with vertical walls between 2 and 4 meters, and roof heights of less than 5.5 meters. Roofs and walls are typically ventilated with varying degrees of automation. The medium level of technology offers a balance between cost and technology.

Greenhouses with a high level of technology are often expensive but are highly productive, environmentally stable, and can significantly reduce the use of energy, water and pesticides. These structures can have roof heights as tall as 8 meters and are clad with double or single plastic films, polycarbonate sheeting, or glass. Environmental controls are almost always automated to ensure constant conditions.

There are two unique greenhouse concepts based on technological classifications. The first is the closed greenhouse concept which is a high technology greenhouse. The second is a screen house which is a low technology greenhouse and can be as simple as screen or mesh placed over a frame.

2.2.1 Closed Greenhouses

A “closed greenhouse” is a greenhouse in which there is no natural ventilation. Instead, it is designed to fully utilize solar energy through daily and seasonal storage [74]. These can generally be classified as high tech greenhouse because of their high level of environmental regulation. The advantages of this system as presented in the literature are improved energy efficiency, water conservation, production rate, advanced control of environment, decreased use of pesticides, and reduced cost [75][76][77]. Middle range greenhouses, in terms of technology, can be semi-closed greenhouses. These greenhouses utilize many of the same principals, but release some thermal energy by natural ventilation. Table 1 gives an overview of four closed and four semi-closed greenhouses studies. Each column of the chart highlights the type, size, thermal management system, advantages and economic performance of eight closed or partly-closed greenhouse studies. This table shows the large potential in multiple areas of sustainable design, ranging from 75% water reduction to 50% energy efficiency improvement. It also shows that the experiments are extremely different in terms of execution and results. This makes it difficult to compare studies and come to a reasonable conclusion regarding the effect of closed greenhouses.

Table 3: An overview of different closed and partly closed scientific reports [74]

Name of Greenhouse Project	Type	Area	Heating	Cooling	Energy Storage	Advantages	Economical Issu	Citation
Aircokas	Semi-closed	700 ha	Heat Pump	Active Cooling	ATES, Buffer	30-45% CO2 emission reduction	Investment can be covered by 20% extra production	[53]
Zero Fossil Energy Greenhouse	Semi-closed	1 ha	CHP, Boiler, Heat Pump	Active Cooling	ATES, Buffer	2% higher production	10% higher cost compared with conventional greenhouse	[54]
Themato	Closed	1,4 ha	CHP, Boiler, AHU	AHU, Active Cooling	ATES, Buffer	17% higher Production, 30% fossil fuel reduction	Cost competitive due to higher yeild	[55]
ECOFYS	Semi-closed	1400 sq. m	Boiler, CHP Heat Pump	Asorption, Chiller, Free Cooling	ATES, Buffer	50% energy efficient improvement, 20% more production, 50% less water consumption		[56]
Energy Producing Greenhouse	Semi-closed	1 ha	Natural Gass, Geothermal, Heat Pump	Active Cooling, Free Cooling	ATES, Buffer	12% higher production	Minimum electrical power cost	[57]
Watergy	Closed	1 ha	Nothing Specified	Natural Convection, Shading	Nothing Specified	75% reduction in water consumption		[58]
GESKAS PSKW & PCH	Closed	160 & 240 sq. m	Co-generation, Boiler, Heating coil, AHU cooling coil, AHU	Cooling Coil, AHU	ATES, Buffer	6% higher production, 34% less primary energy consumption		[59]
ENAS	Closed	9000 ha	Boiler, AHU	Active Cooling, AHU	Battery Storage	Cost reduction for electricity demand for forced ventilation and active cooling		[60]

[78–85]

2.2.2 Screen House

On the other end of the technology spectrum is the “screen-house”. Screen-house refers to the type of greenhouse primarily covered in screen. These can often be considered low-tech because of their susceptibility to the outdoor environment and variable conditions. Screen-houses attempt to maximize ventilation while still providing shade and protection from wind and hail. These structures are effective in saving water, improving temperature and humidity, and protecting crops from insects [86] but, are still susceptible to environmental conditions. Due the lack of control, screen-houses are generally found in mild climates, and house crops that are suitable for the season and environment. The optimal design for implementation of screens with small mesh (0.4 mm or smaller hole size), needed to exclude small insects such as the tobacco whitefly, is a great challenge because the screens significantly reduce air exchange, especially with natural ventilation, but also with mechanical ventilation [87]. Screens have been found to reduce wind speed up to 75% or 95% compared to the outside air [88].

While tightly woven screens protect plants from potential damage, the reduction of airflow from natural ventilation can be an issue. Air temperatures appear to rise significantly when ventilation rates are low [86,89]. However, Fatnassi et al. [90] found that temperature and humidity increase, due to the use of screens, can be alleviated by thoughtful orientation of roof vents and additional side openings. In this study, the authors used computational fluid dynamics to study the dynamics and thermal and water vapor transfer between the crop cover and the greenhouse air. Their results were validated using a tracer gas technique in an experimental greenhouse to test the air exchange rate. These measurements were compared with simulated decay data and found to be in agreement.

Tanny et al. [86] looked at airflow and turbulence in a banana screen-house. A good correlation was found between inside air velocity and external wind speed. The inside air velocity was significantly lower than outside wind speed and was found to have a simple mathematic relationship. Airflow directions inside and outside were similar except for a few exceptions; notably, a southerly external wind created a northerly internal flow.

Raya et al. [91] studied the influence of changes in cover and height on the climate of Canary Screen-houses for tomato growth, finding that the average maximum and minimum air temperatures are more extreme and persist longer in low screen houses (3.5 m high) than in higher ones (5.0 m high). They also found that thermal inversion during clear nights is not unusual.

Screen-houses and closed greenhouses represent two categories of greenhouse technology. Most greenhouses are somewhere in the middle, utilizing natural ventilation as well as mechanical technology. Growers need to balance the cost of initial construction, operation and management with the desired yield and required level of control to determine the greenhouse's level of technology.

2.3 Greenhouse Design Criteria

In general practice, greenhouse design relies on rules-of-thumb and simplified calculations [92]. The National Greenhouse Manufacturers Association (NGMA) publishes rudimentary guidelines for determining greenhouse heat loss, but typical greenhouse projects embody many errors of design. These often go undetected, are tolerated, or fixed in the operations phase by adding extra mechanical systems. Criteria, such as heating, cooling, CO_2 regulation, moisture, lighting and construction, must be considered to create efficient and effective greenhouses. Because of the unique program and schedules for plant production, greenhouses have very different requirements from typical buildings. This creates a unique challenge and opportunity for designers. A large-scale greenhouse represents a dynamic, complex problem in forecasting multiple variables which interact with cascading effects. In terms of thermodynamics and climate control, a greenhouse is much more complicated than a typical building.

Construction components, such as structure and envelope, are important factors to environmental control because they effect heat gain and loss and radiation available for plant photosynthesis. The construction, in turn, determines the heat and cooling loads associated with the controlled environment. In sophisticated practice, greenhouse design procedures are based on proprietary knowledge developed through experience. Industry leaders generally use spreadsheet-based modeling tools which have been refined for many years. There is no single tool that has been widely used or adopted by multiple professionals. This has created a lack of standardization. There is no consistent way to compare simulation results or coalesce the knowledge of these many professionals. Individually created tools are also designed to recognize that different types of crops have different requirements, and include cost estimating.

Typically, greenhouses are controlled through maintaining a specific set point, though these set points are determined based on the culture and type of plant within the greenhouse. Essential parameters of greenhouse climate include temperature, humidity, CO_2 concentration, irradiation, water, and nutrients [93].

2.4 Construction

The shape, orientation, and construction of a greenhouse depends on many factors such as desired produce, location, and the length of growing season [94]. Common construction structures of a greenhouse include the gable, or A-frame roof, and the Quonset, or curved roof, style shapes [92]. Each shape and orientation of greenhouse has its advantages and disadvantages. A series of freestanding greenhouses offer individually controlled environments which allow for environments specifically tailored to the type of plant that they house. The narrower foot print also allows for more efficient natural ventilation. On the other hand, freestanding greenhouses have much more surface area then gutter-connected greenhouses. This makes them more susceptible to heat loss. They require more materials because of the extra walls, and do not use space as efficiently, resulting in less efficient labor [95].

Typically, greenhouses are oriented with the long side running east to west. This maximizes winter sun and heat gains through the south wall. However, this results in a mostly static gutter shadow. Plant located in this shadow may not get as much light resulting in slower growth. This can be avoided by locating walkways in the shaded area. Gutter connected greenhouse are typically oriented north to south to avoid this shadow. With either orientation, rows of plants should run north-south to provide equal light to all plants [96].

The glazing of a greenhouse is held in place by the structure, or frame, which is typically metal in commercial applications. Aluminum is the most common framing material as steel and wood are not durable due to their increased the rate of oxidation and rot in the presence of moisture. Some hoop houses can be framed with PVC but these are typically more temporary structures.

Infiltration is one of the largest components of heat loss. Weather stripping and other insulation materials should be added around doors and vents, between glazing panels and structure and where ever there are gaps in the structure [96].

Another technique that can significantly reduce heating loads is the incorporation of wind blocks. Heat loss from a greenhouse can double in winds of only 15 mph [96]. Wind breaks can be trees, other buildings, fences or anything that reduces air velocity in the vicinity of the greenhouse. Wind breaks are especially effective with old greenhouse with high infiltration [96]. The wind block should be located so that it does not block morning or evening light.

Incorporating opaque walls, insulated foundations, weather stripping or thermal curtains with a high value of insulation can be an effective way to reduce heat loss. In colder climates, a foundation wall, built below the frost line, can help insulate soil within the greenhouse and help prevent surface freezing which could damage the greenhouse's structure or glazing [97]. These low perimeter walls are typically used along with raised benches to reduce the surface area of glazing material without effecting the plants. Similarly, the north can be solid. This might have a slight effect on the light levels, but the reduced heating load is likely more significant [95].

2.4.1 Cladding

Greenhouse cladding is an important aspect of material innovation. Not only is the exterior surface responsible for insulating and protecting the environment, it also needs to allow sufficient solar transition as to provide the plants with adequate light. There is a delicate balance when it comes to greenhouse construction and energy efficiency. The goal is to clad the greenhouse in a way that maximizes light to the plants without negatively impacting the greenhouse energy consumption. This can be done by carefully selecting the best glazing (transparent light penetrating) material and incorporating opaque walls in location that will not shade or effect light to the plants. Common glazing materials include glass, acrylic, polyethylene fil, polycarbonate and fiberglass [95], [92]. The number of material layers and the type of gas in the panel cavity effect their insulative properties. Double layer glazing with at least a ¼ inch of air or gas between material layers can reduce heat loss by up to 40% [96]. A well-insulated type of glazing provides the advantage of less heat loss but also limits the amount of solar radiation that reaches the plants. To most effectively design the greenhouse cladding, it is important to understand the cultural requirements of the plants. For example, it would be beneficial to know if the crop intended for the space can withstand colder night temperatures but need high intensity light. In this case, it would be more beneficial to use a material with high transmission even if it means sacrificing insulative value.

To achieve the highest efficiency through cladding material, it is important to carefully weigh the options regarding needs of the plants. There are trade-offs with any type of cladding. Transmission of both light and heat, insulative properties and the life expectance must be Plastic films and non-reflective glass coatings have been found to scatter the light without reducing the transmittance of the surface. Recent research on cucumber production [98] has shown that diffusing cover materials improve the uniformity of vertical light distribution in a crop. This decreases the intensity of light on the uppermost crop layer and allows light to penetrate to the underlying leaves. These properties lead to an increase in production up to 10%. Films with colored pigment are also an area of study. These films reflect or absorb the non-photosynthetic wavelength of solar radiation and transmit solar radiation for efficient plant growth [87]. Similar technologies such as liquid radiation filters have been investigated since 1996 [99].

Thermal or infrared transmittance is also an important consideration. Heat is transferred into the space at a different wavelength then visible light and thus does not necessarily have the same transmittance value. In hot climates, it is beneficial to block infrared wave lengths to limit heat gain while in cold climates the heat gain is typical beneficial during winter months.

Material	% Light Transmission	U-value	% Thermal Transmission	Life Expectancy
Glass				
Single	88-93	1.1	3	25+
Double	75-80	0.7	<3	25+
Acrylic				
Single	90	1.1.3	<5	30+
Double	84	.49-.56	<3	30+
Polycarbonate				
Singe	90	1.1	<3	10.0-15.0
Double	78-82	.53-.63	<3	10.0-20.0
Triple	74-76	.42-.53	<3	10.0-20.0
Polyethylene Film				
Single	87	1.2	50	3.0-4.0
Double	78	0.7	50	3.0-4.0
Double wit	78	0.5	<20	3.0-4.0

Table 4: Comparison of Glazing Materials and their Properties (Source: Energy conservation of Commercial Greenhouses (NRAES-3) and product literature: as cited in Stanford, 2011)

The final consideration is the life expectancy of the covering material. Typically, glass or acrylic panels last between 25 and 30 years while Polyethylene films only last for 3 or 4 years. This has both economic and environmental implications. Table 2 give a comparison of glazing materials and their properties.

Thermal curtains can be incorporated as a method for reducing the heat loss at night. These removable devises retain heat by acting as barrier between the space occupied by the plants and the roof or walls [95]. Thermal curtains can be controlled automatically or manually and can also serve as shading devises during the summer months.

Screens have also been widely analyzed to optimize insect protection and natural ventilation. The use of screens is a challenge because screens with a small mesh (.4 mm or smaller) are needed to protect from small insects, but these also significantly reduce air flow [87]. Santos et al. [89] studied climatic conditions in screen houses with tomatoes in Tenerife, Canary Islands and found that denser screens can induce higher mean air temperatures and that dust deposition on the screens can alter light transmission by as much as 17%. Oren-Shamir et al. [100] used colored screens, instead of the conventional white or black screens, to manipulate the crop vegetative growth and improve the yield and quality of the crop. They found that colored shade nets can improve the yield and quality of certain species because with colored screens, the spectral manipulation is aimed at specifically promoting desired photomorphogenic/physiological responses and light scattering improves penetration into inner canopy. Romacho et al. [101] studied the growth and yield of cherry tomatoes in net-covered greenhouses. They experimented with a variety of net colors and reported transmission values of 62% for a clear and 58% for a green, 15 mesh screen house [22][147][147]. In a similar study, Castellano et al. [102] researched the relationship between solidity ratio, color, and shading effect of agricultural nets.

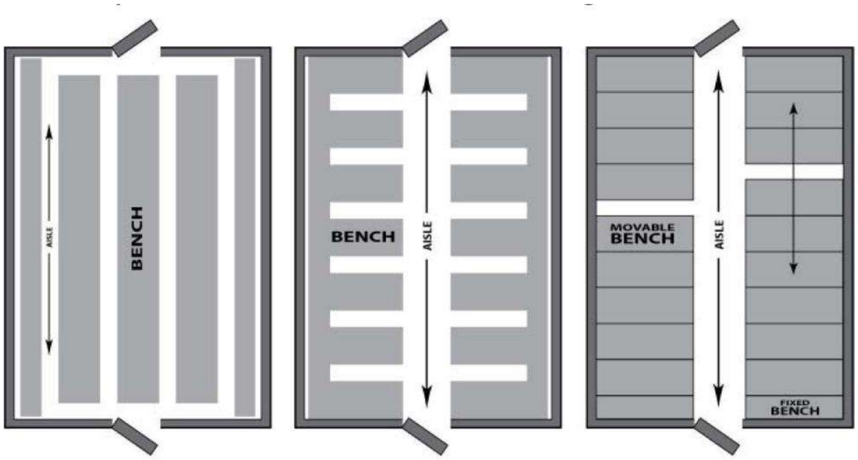


Figure 5: Growing area percentage in a 30 x 96 foot greenhouse: Longitudinal layout (left)-64%, Peninsular layout (middle)-70%, Movable (right)- 84% (Source: Stanford, 2011)

2.4.2 Space Utilization

Increasing the number of plants in a space reduces the energy per unit [95]. The layout of a greenhouse needs to maximize space utilization while still allowing for workers to more round effectively. This reduces the volume of space that requires conditioning and increased efficiency. Figure 2 demonstrates several different layouts and their associated efficiency. The layout on the right side represents maximum efficiency. In this case, benches role on top of fixed supports, this allows benches to be places directly side by side. Workers can role the benches over to access each one in turn.

In a high-tech greenhouse successfully controlling a greenhouse becomes an important part of operation efficiency. Automated controls allow the greenhouse systems to react to outdoor conditions automatically. For example, light sensors can automatically trigger supplementary lighting based on the amount of natural light. Only recently has this field become a major part of greenhouse operation. These systems are important because utilizing energy efficiency strategies in greenhouse design and operation is the key to making them financially and environmentally beneficial.

As an example, Guterman Greenhouse, working with Cornell University Agricultural Experiment Station retrofitted all greenhouse lighting and environmental controls throughout 47 greenhouses. New dimmable high pressure sodium lighting replaced on/off metal halide and is controlled by a technical environmental control system that also operate the heating and cooling systems. This retrofit resulted in $337,000 and 386 tons of carbon per year [103].

One study by Van Beveren et al. [104] found that energy can be saved by relaxing temperature and humidity bounds. In this study a dynamic optimization tool based on optimal control theory was used to obtain tends in the transfer of energy that minimized the energy input. Although it seems obvious that increasing acceptable temperature and humidity range reduced energy consumption, the quantification of this measure is very valuable.

2.5 Lighting

Supplemental light helps to produce healthier plants with higher yield and to shorten the time from planting to market. Controllable lighting also makes it possible to induce flower and predict more accurately when a crop will be ready for harvest. These are important aspects of greenhouse operation because shortened growing time and reliable harvest helps to limit time spent heating, cooling and ventilating and thus reduces the energy intensity per crop.

There are several types of supplementary lighting used in greenhouses. These include fluorescent lamps, high-intensity discharge (HID) lamps and light emitting diodes (LED). Hight-intensity discharge lamps are most commonly found in greenhouse operations. These can be categorized as either high-pressure sodium (HPS) or pulse-start metal halide. Of these two types of HID lamp, HPS are more energy efficient. Most recently LEDs have been applied to the greenhouse environment. LEDs are both more efficient and offer a degree of control that is not possible with their predecessors. LEDs emit a much more specific wave length of light. Plant growth can be manipulated by exposure to different wave lengths of light.

As with other components of the greenhouse it is important to understand the lighting requirements of the plants that are grown in the greenhouse to maximize the efficiency of the lighting system. Ideally, plants are exposed to just enough light to keep them healthy and maximize yield.

Light-emitting diodes (LEDs), as potential source for greenhouse lighting, open up a range of new possibilities. LEDs produce light in a very narrow wavelength range which emit very little heat radiation. Any heat produced is due to the lights limited energy conversion efficiency and can be drawn away with convective cooling. As a result, LEDs can be applied in areas of the greenhouse that do not receive sufficient light, without increasing the cooling load significantly. In theory, this type of intercrop lighting could significantly increase crop photosynthesis [105].

Another LED study, conducted by Singh et al. [106], focuses on the potential of LEDs to replace traditional light sources in the greenhouse. They conducted an economic analysis of traditional vs. LED lighting to show that the introduction of LEDs will reduce the production cost of vegetables after several years. Benefits of LEDs include high energy efficiency, low maintenance cost, and longevity. The specific plant response to different wavelengths is discussed below, but, more detailed scientific studies are needed to understand the effect of different spectra on plants growth.

Nelson and Bugbee [107] reported on the “photosynthetic photon efficiency and photon distribution pattern of two double-ended HPS fixtures, five mogul-base HPS fixtures, ten LED fixtures, three ceramic metal halide fixtures, and two fluorescent fixtures.” The two most efficient LED and the two most efficient double-ended HPS fixtures had nearly identical efficiencies at 1.66 to 1.70 micromoles per joule. They found that the fixtures are an improvement over the 1.02 micromoles per joule efficiency of the mogul-base HPS fixtures that are commonly used. The best ceramic metal halide had an efficiency of 1.46 and fluorescent fixtures of 0.95 micromoles per joule. This study calculated the initial capital cost of fixtures per photon delivered and determined that LED fixtures cost five to ten times more than HPS fixtures. After five years’ electricity plus fixture cost per mole of photons is thus 2.3 times higher for LED fixtures due to high capital costs. They concluded that the cost per photon delivered is higher in these systems, regardless of fixture category.

The wavelength specificity of LEDs can have a dramatic effect on plant anatomy and morphology, as well as nutrient uptake and pathogen development. This concept has been examined for many years by researchers such as Caldwell [108] and his study of solar UV radiation and the growth and development of higher plants. Designing a lighting system that provides sufficient light in wavelengths essential for growth of specific crops has presented a significant challenge [109]. Much research has gone into finding the proportion of blue light required for normal plant growth as well as the optimum wavelength of red and the red/far-red ratio [110–113]. More recently, studies of the effects of greenlight have also found their way into research, finding that greenlight can be effective at penetrating further into the canopy but also a visual aid for workers [114,115]. The addition of greenlight makes the plants appear more naturally to humans and helps with detection of issues or crop ripeness [115]. Geometry of light delivery and timing of different wavelength applications has also become a relevant subject. Okamoto [116] developed an apparatus specifically designed for plant growth which utilized combinations of red and blue lights.

Even LEDs have their limitations. Compared to florescent or HID lights, LEDS convert a larger portion of applied energy to light, but the majority is still rejected as heat. In a high-density situations, this heat must be removed in order for the lights to perform at their peak efficiency and avoid burning out. One forward looking company, Plenty Unlimited, has designed a fixture which circulates chilled water directly through the manifold of the light. This has the combined effect of maintaining a high performance temperature for the LEDs and reducing the cooling load for the HVAC system by preventing heat from entering the space. As demonstrated by Plenty, LED technology continues to develop. As LEDs become more prevalent and the cost declines, they become a more cost effective and viable option for greenhouse growers.

2.6 Heating Systems

The horticultural industry had recently make an effort to reduce fossil fuel consumption and replace traditional heating systems with renewable sources [85]. As demonstrated in Figure 1, there is a push towards alternative energy and a quickly changing greenhouse industry. A few of these renewable energy systems applied to greenhouse heating include the use of ground source heat pumps, fuel combustion, solar heating, and waste heat technologies [117]. Research regarding these systems demonstrates that there is great potential in the use of alternative heating strategies for reducing the cost of energy and the fossil fuel emissions of greenhouses.

2.6.1 Combustion Systems: Biomass

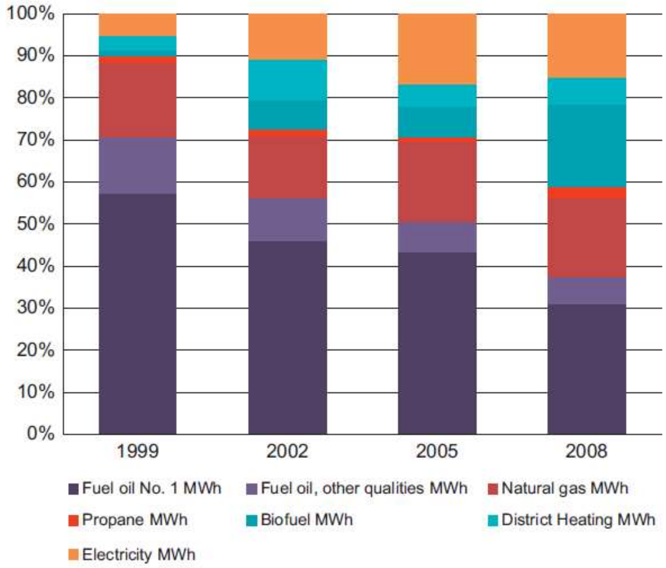


Figure 6: Trend in greenhouse fuel used in Sweden, 1999-2008 (Vadiee et al. 2015)

Biofuel is quickly becoming one of the most commonly utilized renewable energy sources in greenhouse applications. These combustion systems range from simple pellet stoves to large outdoor boilers with forced air heat exchangers [118]. Biomass is considered greenhouse gas neutral when converted to heat energy [119]. Figure 3 depicts the trend in green house fuel uses in Sweden from 1999-2008. It can be seen that fuel oil has decreased by nearly 25% while biofuel has increased by 20% [3].

Biofuels as a viable energy source for green house heating has been researched and implemented on many occasions. In Alabama, Fasina [120] determined that a biofuel pellet/furnace combination can maintain the temperature of a standard 24 ft. by 96 ft. greenhouse at 65 F or higher with energy savings up to 64% depending on biofuel type.

Besides acting as a sustainable heat source, the off-gassing from biofuel combustion can be used as CO_2 enrichment. Unfortunately, this is still a challenging and expensive option. Biofuel produces higher volumes of particulate matter and ashes than other fossil fuels and must be conditioned before it can be utilized for enrichment [121].

2.6.2 Fuel Cell

Vadiee et al. [3] investigated the feasibility of integrating a proton exchange membrane fuel cell (PEMFC) system into a commercial greenhouse. A PEMFC is an electrochemical energy conversion device that converts the chemical energy of a reaction directly into electricity with byproduct of water and heat. Their study assesses the mutual benefits on performance that the greenhouse and PEMFC system had on each other. The main objectives were to recover the low-quality waste heat of the PEMFC system to meet the thermal energy demand of the greenhouse. Energy analysis was conducted to evaluate the energetic performance of the system. The system model was developed using TRNSYS, and a sensitivity analysis varying the main influencing operating parameters was performed to evaluate an optimal configuration of the system, testing the impacts of temperature and air stoichiometry on performance of the system. This study found that a 3-kW fuel cell system is capable of providing 25% electricity and 10% heat demand for a 1000 m^2 commercial greenhouse for a year.

2.6.3 Solar Heating Systems

Solar greenhouses are designed to make use of the sun. As solar radiation hits the exterior and interior surfaces of the greenhouse, much of its energy is converted into thermal energy. This can be a positive effect in cold climates but can also make it very easy to overheat the greenhouse in hot climates. There are several systems that take advantage of the thermal solar energy and store it for colder parts of the day when the greenhouse needs to be heated.

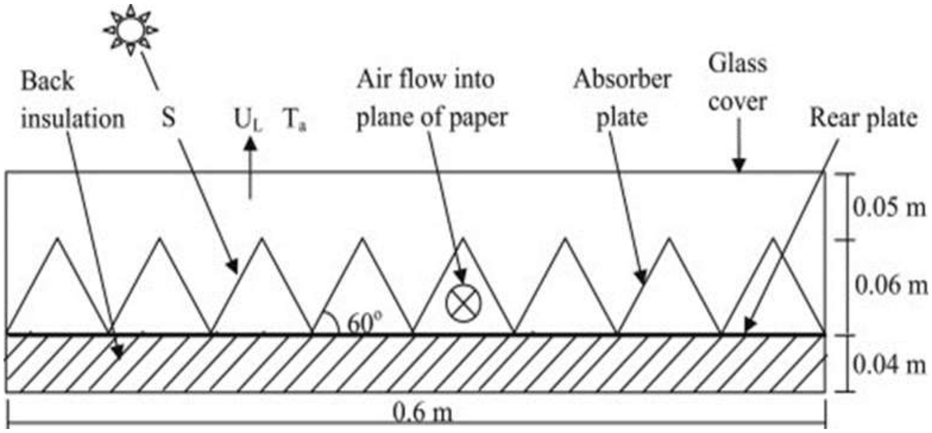


Figure 7: V-Corrugated Solar Air Collector (Joudi and Farhan 2014)

Joudi and Farhan [122] studied the use of solar air heaters (SAH) on the roof of a single sloped greenhouse in Baghdad, Iraq. The SAHs used in this study were single pass air heaters with a “V” corrugated plate absorber and a glass cover as shown in Figure 4. Solar air heaters can be used in two ways: for direct supply of hot air to the greenhouse, or for supply of heat to a thermal energy storage system for later use during the cooler nighttime. It was found that the SAH system could produce up to 146% of the daily heating need for the greenhouse in question. Excess heat on clear days can be directed towards soil heat storage for use during the nighttime. Because of this excess of heat, it was calculated that covering roughly 45% of a greenhouse’s roof with SAH could meet 100% of the heating demand for the building in question. This study also emphasizes the importance of including soil surface heat gains within calculations which allow theoretical and experimental values to align more closely.

Ghosal et al. [123] conducted an experiment comparing the effectiveness of a ground air solar collector verses an earth air heat exchanger for greenhouse climate control in Delhi, India. In this study, a length of air filled tubes was placed underground where the temperature remains relatively constant. As air passed through the tubes, heat was exchanged between soil, tubes and air. The ground air collector consisted of a solar, flat plate collector which transferred energy to pipes buried in the sub-surface of the ground. A numerical model was developed and used to predict and compare thermal performance of a greenhouse using each of the systems. The program results were validated through experimental data collected on several clear and sunny days. Results show that the solar collector was more suitable for the climate and that greenhouse temperatures were 2-3 degrees higher than with the earth heat exchanger and the greenhouse experienced less temperature variation.

2.6.4 Systems Utilizing Waste Heat

Other greenhouse heating systems include the use of waste heat in the form of air, water, or flue gases from industries to keep a greenhouse warm in the cooler months [124]. Due to inherent inefficiency, industrial processes and power generation lose a large percent of their productivity to waste heat. Waste heat is "heat that is either lost through the flue stack of an industrial operation, or which is rejected from a power generation station to improve the thermodynamic efficiency of the cycle" [2]. Although it is not technically and economically feasible to recover all waste heat, a gross estimate is that waste-heat recovery could replace 9% of total energy used by US industry [125]. Instead, waste heat is often discharged into nearby streams, rivers and other heat sinks, creating many ecological issues. Utilization of this heat through greenhouse heating can offset the cost of cooling industrial equipment, as well as have a beneficial environmental impact [126].

One feasibility study conducted by Rotz [127] for a potential greenhouse in Pennsylvania, used simulation to compare the cost and energy consumption of five different heating systems. The computer model used a combination of weather simulation and a greenhouse model to determine fuel and electrical needs based on calculated heat losses and gains from convection, sensible and latent ventilation and solar. Degelman [128] created the weather component of this simulation which predicted temperature, dew point, solar insolation, wind velocity every hour for a year. In the combination of weather and greenhouse model, the heat losses and gains were balanced to find the excess or deficiency of heat in the greenhouse each hour. Using this model six systems where compared. A traditional oil-fired boiler was the standard or baseline by which gage the energy improvement of five nontraditional systems. The nontraditional systems were two hot water systems, and three warm water systems as shown in Table 3. Table 3 gives an overview of the six systems that were analyzed and the economic results. It is clear from the table that boiler assisted, warm water system had the greatest savings at 51 percent. The boiler assisted hot water system had the lowest pay-off ratio of 4.8.

Table 5: Cost of heating a 13,000 square meter greenhouse with conventional and waste heat systems (Rotz, 1979)

System	Equipment	Energy Costs ($/sq. m/ yr)	Total	Percent Savings	Pay-off Ratio Year
Conventional					
Oil-fired Boiler	1.04	10	11.04	-	-
Hot Water (65 to 100 C)					
Boiler Assisted	2	5.01	7.01	37	4.8
Heat Pump Assisted	4.13	9.35	13.48	-	-
Warm Water (13 to 50 C)					
Heat Pump Assisted	3.58	3.49	7.07	36	10.2
Two Stage Condenser	2.38	3.94	6.32	43	6.6
Boiler Assisted	2.38	3	5.38	51	5.5

Another instance of waste heat utilization is RWE's Horti-Therm project in which cooling water heats greenhouses. The Horti-Therm technology, developed by German energy supplier RWE, has successfully delivered waste heat to greenhouses and asparagus fields for more than 30 years. Heating systems were designed to cover a temperature difference of 30 degrees or +18 °C inside air temperature to -12 °C outside air temperature. The worst observed weather conditions during monitoring period were – 14.3 °C outside air temperature, low solar emission, relatively high wind speed and snow fall. The system covered the heat demand under these conditions without any problem [129]. The early technology, initially monitored in 1988, has recently been reconfigured based on the evolution of modern power plants and the fact that they use waste heat to increase power. “Birgit and Michael Bong are testing its successor, Horti-Therm Plus, in their greenhouse in Niederaußem, in collaboration with RWE engineers and project partners” [130]. The new system needs a flow temperature of 20 to 30 degrees Celsius in order to be sufficient [2]. The pilot project is designed as research into the intelligent use of cooling water. Whether the new technique works is still undetermined since there is no heating load this time of year [130].

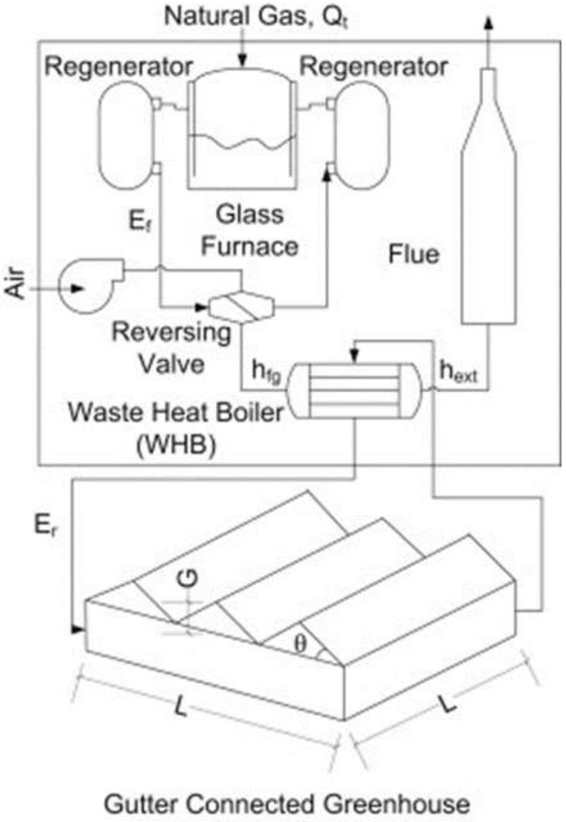


Figure 8: Schematic of industrial waste heat system (Andrews and Pearce 2011)

Walker [131] created an experimental greenhouse heated by power plant cooling water. The heating system used nozzles to spray heated water on the outside of the greenhouse. Two experimental greenhouses were constructed near the power plant. One was heated and one was used as a standard by which to measure the effect of the surface heating system. The major benefits of the system included low capital costs and no increase in greenhouse humidity because greenhouse air didn’t contact the water. A flow rate of 0.094 L/s per m^2 of greenhouse area was found to be sufficient to heat the greenhouse to 15 °C using 30 °C water.

Waste heat greenhouse developmental work was conducted in Alabama on a pilot-scale greenhouse at Muscle Shoals by Burns et al. [132]. This study used an electric boiler to simulate condenser cooling water temperatures. The greenhouse studied was a conventional 7.3- by 30.5-meter glass-glazed structure equipped with a waste heat environmental control system. A direct-contact evaporative pad was used for heating by recirculating saturated air through the evaporative pad over which warm water flowed. The system could also cool the space by venting greenhouse air to the atmosphere, and pulling ambient air is through the pad system. The amount of heating or cooling was controlled by louvers allowing either recirculation or venting of the greenhouse air and fin-tube heat exchanger to be available for use in reducing greenhouse relative humidity.

In the research of Andrews and Pearce [2], the feasibility of using waste heat, or flue gas, produced from the glass industry in heating greenhouses was tested. The system proposed by the study makes use of a waste heat boiler connected indirectly to the glass furnace. Figure 5 shows a schematic of the industrial waste heat system. It was concluded that not only are waste heat greenhouses feasible, they are less expensive to heat and can offset thousands of tons of CO_2 annually when compared to conventional natural gas heating systems. However, because waste heat is not consistently available, supplemental fuel sources may be necessary, such as a natural gas boiler. The research presented is based on calculations and not necessarily experimental values. For further advancement of the waste heating system with greenhouses, an experimental study should be performed.

Utilizing waste heat from data centers is also becoming more common as a source of heat for greenhouses. Pervilä et al. [133] studied the possibility of using waste heat from a data center to heat a small greenhouse attached to the building's roof. A prototype greenhouse was built as a destination for waste heat generated by the data center and was located on the roof of the building to avoid taking up additional space in an urban environment. Because nearly all energy used by the data center's servers is converted to heat, hot air, or waste heat, this energy can be exhausted directly into the greenhouse. Plants could be successfully grown in this greenhouse using this method. The main limitation to this study is that the prototype's small size only allowed it to be operational for part of the year. Larger data centers and bigger greenhouses may have the potential to be used year-round.

Denzer et al. [124], used EnergyPlus to model the environment of a greenhouse and concluded that the amount of waste heat available from a sugar processing plant in Lovel, WY is sufficient to provide annual heating demands for a 3-acre greenhouse. A water to air heat pump system utilizing waste heat the waste heat from this facility can save 74% of total annual site energy for the greenhouse heating.

2.7 Cooling Systems

In hot, humid climates, efficiently cooling greenhouses presents a significant challenge. Common systems include variable air volume or chiller technologies, but this review looks at innovations that are geared towards reducing energy consumption. Natural ventilation and evaporative cooling are systems designed to draw thermal energy from the interior space, while liquid radiation filters attempt to limit the amount of thermal energy that enters the greenhouse environment.

2.7.1 Natural Ventilation

Natural Ventilation is one of the most highly studied techniques for greenhouse cooling. Many different window, vent, and opening configurations have been studied to find the optimal air circulation and flow through a greenhouse based on different locations and climates.

Ventilation directly impacts greenhouse air temperature and CO_2 levels, both of which are essential parameters in successful growth of a greenhouse crop [94]. For many greenhouses, natural ventilation is used as the primary method of cooling [134]. This method is efficient and uses very little, if any, additional energy [135]. When vents are placed near the base of the greenhouse and near the roof, natural ventilation is the process of releasing the hot air through the top vent of the greenhouse and drawing in cooler air through the bottom vent.

Other ventilation systems are considered “forced ventilation” systems. These systems are similar to natural ventilation, but make use of fans and blowers to increase the number of air changes through the greenhouse [135]. Forced ventilation uses more energy, but has the potential to significantly reduce greenhouse temperatures.

Many ventilation studies involve the use of computational fluid dynamics. Peña et al. [136] performed a computational fluid dynamic analysis to optimize the ventilation performance of an Almería-type greenhouse. They evaluated different parameters including width, span number, vent area, location, type of vent openings, plant occurrence and presence of screens with different porosities using a commercial program ANSYS/FLOTRAN v8.0. This study found that ventilation rate was reduced by 88 percent when span number was increased from one to five or the greenhouse width increased from nine to forty-five feet and the use of insect screens decreased ventilation rate by 50 percent. The presence of plants in the green house caused the air near the floor to reduce in speed.

Another computational fluid dynamics study tested the effect of structural modifications and the orientation of a fixed open ridge in order to optimize ventilation for a Colombian multi-span greenhouse [137]. The goal was to maximize the air exchange rate and improve the movement within the greenhouse while maintaining the highest degree of temperate and moisture homogenization. Similarly, Baeza et al. [138] studied the effect of ventilator size on natural ventilation in Parral greenhouses through computational fluid dynamics. Esteban et al. [139] analyzed the role of sidewall vents on buoyancy-driven natural ventilation in greenhouses with and without insect screens and Baeza et al. [140] used computational fluid dynamics to study natural ventilation in relation to number of spans and roof vent configuration.

Two general types of rooftop ventilation have been extensively studied. The first is windward ventilation in which the stream of air enters directly into the space. The second is leeward ventilation in which air climbs to the top of the roof and enters through an opening on the low-pressure back side.

Windward

While windward ventilation offers a more intense air exchange and ventilation rate [141], it has the drawback of creating a circular air flow where entering air, travels along the roof and exits through the second ridge before mixing with the internal air [142]. In hot climates, windward ventilation is preferable when mixing can be achieved.

In an attempt to achieve optimal air flow in a space cooled by windward ventilation, Montero et al. [143] studied the effect of deflectors and ventilator configurations in a crop protection structure for the tropics. Their study proved the efficiency of an air deflector on a jack-roof ventilator to avoid the passing of air through the roof vent.

Nielson et al. [144] studied natural ventilation of a greenhouse with top screens, another method for increasing the mixing of windward ventilated air. He utilized a method which directed the passing air at the hinged ridge vents into the crop space using a 1-m high vertical screen mounted on the ridge. This improved the air exchange in the plant zone by about 50% on average. He also found that increasing the roof slope helps to direct the incoming air to the crop area. Another study on greenhouse roof slope found that ventilation sharply increased with slope up to 25 degrees [138]. Steeper slopes did not have great effect on the air exchange rate and internal flow.

Side wall ventilation is similar to windward ventilation since air enters directly rather than in the lee of the wind [145]. However, in a comparison of windward verses side vents [136] found that the side vents had higher air exchange rate while the windward had better temperature distribution. Kacira et al. [146] performed computational fluid dynamic simulations to investigate the effect of side vents in relation to the span number of a gothic greenhouse with a continuous roof vent on the leeward side of each ridge. Results showed that when both sides were fully open the ventilation rate increased and the ventilation rate decreased exponentially as the span number increased.

Leeward

For cooler climates where a slower exchange rate is acceptable, leeward ventilation offers a more uniform air distribution [145]. Mistriotis et al. [147] performed a computational fluid dynamic simulation of 32, 64, and 96 meter-long greenhouses. The behavior of the 96 m greenhouse was different from the others, as a second outflow occurred at the back of the greenhouse. Similarly, Reichrath and Davies [148] used CFD to model the internal climate of greenhouses for both leeward and windward vents. They confirmed the occurrence of reverse flow in the windward part of the greenhouse and of a dead zone with low velocity at approximately 60% of the total glasshouse length for a very large Venlo type greenhouse of 60 spans.

2.7.2 Evaporative Cooling Systems

There are several types of evaporative cooling systems that work well for greenhouse applications. Evaporative cooling is the reduction in temperature resulting from the evaporation of a liquid. When the liquid (generally water) evaporates, it removes latent heat from the surface or media from which evaporation takes place. These systems have limited potential in climates with high relative humidity. The efficiency of the system is determined by the difference in wet and dry bulb temperatures; therefore, humid air does not have as much capability to evaporate moisture.

The most common type of greenhouse evaporative cooling system is the fan and pad system. Fan-Pad systems consist of a 4-6 inch-thick cellulose pad exposed to either natural or forced ventilation. Overhead pipes supply water which evenly wet the pad. As the pad is exposed to ventilation, evaporation occurs. In an experiment by Kittas et al. [149], Fan-Pads, along with the use of shading devices, were found to achieve 80 percent efficiency and was able to maintain a temperature as much as 10 degrees cooler than the outdoors. They also found that some condensation occurred on soil surface early in the day. Their experimental data was compared to results from an analytic model which described the greenhouse as a heat exchanger. The model also suggested that the shading could be avoided in dry climates because of the increased potential of the evaporation. Sabeh et al. [150] studied the water use of a fan and pad evaporation system for greenhouse cooling in arid climates. Other studies examining fan-pad systems have been conducted by Bucklin et al. [151] and Jain and Tiwari [152].

Evaporative Fog cooling is a process in which water is sprayed in a very fine mist without wetting the foliage. The evaporation of the tiny droplets lowers the temperature of the greenhouse environment [153]. Ventilation plays a major role by helping to control humidity and evaporation rates. Abdel-Ghany and Kozai [154] studied the environment of a naturally ventilated and fog-cooled greenhouse. Their study involved a dynamic model which consisted of a system of equations solved numerically using predictor-corrector technique and the iteration procedure for the algebraic equations. They included parameters such as meteorological conditions and thermos-physical (plan, cover, air and soil) properties. The results of this model were compared and found very close to the experimental values. Abdel-Ghany and Kozai [154] was limited to one type of evaporative mechanism. They concluded that more research should be done to assure that the fog evaporates during the fogging cycle to reduce condensation on the plants.

Arbel [153] studied ventilation and evaporation flow rates necessary to achieve the desired environment given the solar radiation and the ambient climate conditions. They created a mathematical model which was later verified though data collected from experimental greenhouses. They found that the fog system can provide a wide range of temperature and humidity more consistently than a pad and fan system. What is more, they found that fog did not greatly affect the radiation inside the greenhouse.

Other studies have experimented in order to improve evaporation strategies. Giacomelli et al. [155] experimented with a blanket mesh to replace the pad as an evaporation surface. The typical drip wetting system was replaced with a misting spray which more evenly saturated the evaporation surface. They found that the fog and blanket combination had greater evaporation rates and was able to maintain a temperature up to 10 degrees cooler.

2.8 Systems with Heating and Cooling Capability

In climates with hot summers and cold winters, greenhouses need both heating and cooling systems to provide acceptable environments for growing plants. In these locations, it makes sense to incorporate an HVAC system that is capable of adding and removing heat from a space. Covered in this section are liquid radiation filters, earth tubes, heat pumps, thermal energy storage, and in-floor radiant systems.

2.8.1 Liquid Radiation Filters

This advanced technology involves circulating a liquid radiation filter (LRF) through the cladding of a greenhouse. The liquid filter removes infrared waves in the range of 700nm of solar radiation, while photosynthetic radiation (400-700nm) is transmitted into the greenhouse [156]. This system is designed to reduce the heat entering the greenhouse during the day and allow the heated liquid to recirculate, cool, and maintain the temperature of the greenhouse through the night. Feuermann et al. [156] conducted a simulation to study the relationship of design of the LRF system and the thermal performance of the greenhouse. The simulation results were validated and found to be within one or two degrees Celsius of performance data from a greenhouse in the Israel desert. The study determined that the use of the liquid radiation filter allowed the greenhouse to remain closed about two thirds longer during the summer months. This is beneficial in terms of reduced cooling load, limited contamination and CO_2 fertilization. Feuermann et al. [157] followed up with a study of LRF for greenhouse application in a desert environment.

Canham [158] performed experiments which showed that LRFs proved practical and could be automatically controlled by a thermostat. He experimented with different emulsions to test the effective shading. LRFs have also been used in cultivation of plants in brackish water [159]. Many other related research experimented with a similar idea of a "fluid-roof greenhouse"[99,160–165].

2.8.2 Earth Tubes

Ghosal et al. [123] modeled a greenhouse with an integrated earth to air heat exchanger. The model was a MatLab representation of a greenhouse located in Delhi, India, utilizing a recirculation type earth to air heat exchanger. Temperatures of the greenhouse were about six to seven degrees warmer in winter and three to four degrees colder in summer. These results were validated with measured values. They provided an excellent table that summarizes 16 studies analyzing the performance of heat exchangers. The remarks column suggests how well the greenhouse performed in terms of heating, but does not comment on the cooling benefits.

2.8.3 Ground Source Heat Pump

Many studies have been conducted regarding the use of ground source heat pumps as a method of environmental regulation. The efficiency of a ground source heat pump can be influenced by many factors such as depth of the ground loops, length of the tubes, and type of ground heat exchanger.

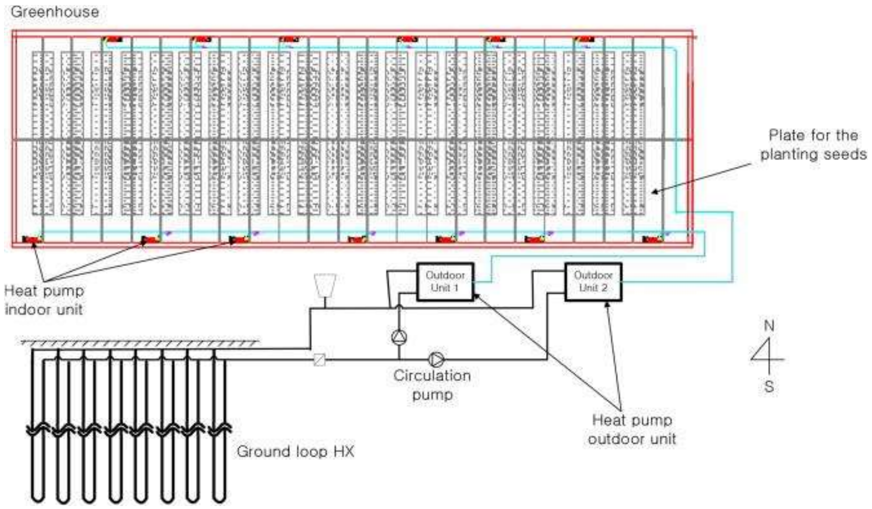


Figure 9: Schematic of Ground-Coupled Multi-Heat Pump System (Choi et al. 2014)

Choi et al. [166] studied the performance of a ground-coupled multi-heat pump system in a greenhouse. The system consisted of a closed-loop vertical ground loop heat exchanger and indoor and outdoor heat pump units. A system schematic is shown in Figure 4. The authors of this study report that ground-coupled multi-heat pump systems can be incorporated with many types of indoor heat pump units. This paper is limited by the fact that only heating was explored in the study, though the author states that both heating and cooling can be achieved with a GSHP. The authors also call for future studies to explore creating a load calculation algorithm for greenhouses and an algorithm to control circulating air flow rates within the greenhouse to maximize energy savings.

Ozgener and Hepbasli [167] conducted a study which attempted to relate the thermodynamic and economic feasibility of ground source heat pumps for greenhouse application. They used exergoecomics to search for the optimal design of a compressor condenser to be used in a conventional vapor-compression heat pump [168].

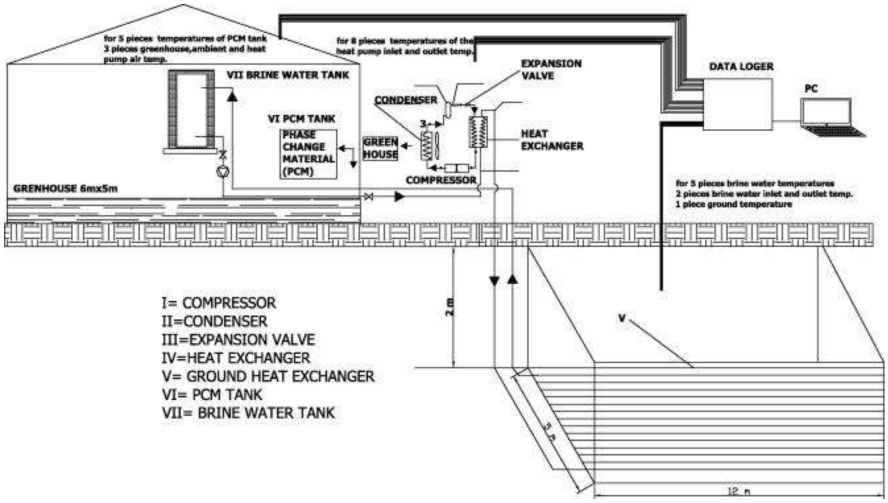


Figure 10: Schematic of GSHP-PCM System [20]

Benli [169] studied the use of a ground source heat pump with latent heat storage for use in greenhouses. The system involves a heat pump and phase change material as key components, along with other necessary components such as pumps, piping, control units, and water tanks. A schematic of the system design is shown in Figure 7. The study concluded that the system could run quite efficiently and distribute heat evenly. They also found that placing the heat pump inside the greenhouse rather than outside would help prevent freezing. Still, additional heat sources may be necessary for sudden temperature changes or extreme cold nights. The author also suggests that a combination of two heating systems could be used to meet the heating load of a greenhouse in climates such as Turkey.

2.8.4 Thermal Energy Storage (TES)

Thermal energy storage (TES) is a technology that stores energy by heating a material so that the stored heat can be used later. The energy storage of a material is based off the specific heat of the substance. This means that materials with high specific heat can absorb much more heat without changing temperature. This is useful in greenhouse and other applications because the TES material will absorb heat during warm hours (removing it from the space) and release heat during cool hours (adding it to the space). In greenhouses with very little insulation, thermal energy storage helps to maintain a constant temperature.

TES technology is always found in conjunction with another type of heating or cooling because it is a method of storing heat to be used later, and does not actually produce heat. Santamouris et al. [170] discussed 5 types of solar greenhouses that make use of TES systems. These include water storage, latent heat storage, rock bed storage, soil storage with buried pipes, and other types of heat storage. They surveyed 95 solar greenhouses in an attempt to analyze the most effective thermal storage for a passive solar greenhouse. Their paper, “Passive solar agricultural greenhouses: A worldwide classification and evaluation of technologies and systems used for heating purposes,” published in *Solar Energy,* provided three excellent tables that summarize greenhouses using rock bed, PCM, and water for heat storage. These tables summarized the wide variety of studies conducted and the similarly large variety in results. They found that water storage with ground tubes resulted in an air temperatures 2-4°C higher than the minimum outdoor air temperature and water barrels could generally satisfy 70-75%

of the annual heating needs, achieving an inside temperature 2-10°C higher than the ambient temperature. The use of water tanks could bring the inside temperatures to 2-15°C higher than night outdoor temperatures and cover 20- 50% of the annual heating requirements. Latent heat storage could satisfy 20- 75% of the annual heating needs but, depends on the size of the greenhouse and the storage, location, type of cover material, and the type of the cultivation. Buried pipes on average satisfy 30-60% of the annual heating with temperatures 3-10°C higher than the minimum outdoor temperature. Rock bed storage could satisfy 20-70% of the annual heating requirements and achieve inside temperatures ranging 4-20°C higher than the minimum ambient air temperature, however, installation of the underground heat storage, could be more expensive and difficult.

In another study, Santamouris et al. [171] monitored a passive solar greenhouse for two years to determine the effect of a TES wall located on the north aspect and a network of earth to air heat exchangers buried in the greenhouse. The goal of the two integrated passive elements was to reduce heat loss and increase the usefulness of the solar gain. They found the passive systems reduced the heating requirements of the 1,000-square meter prototype greenhouse by 35%.

2.8.5 Efficiency in distribution

The method of heat distribution can also drastically effect efficiency. Because heat rises, temperature stratification will occur if the air is not sufficiently mixed. Energy for fans and mixers can be a major detriment to greenhouse efficiency. One solution to this is to supple the heated or cooled air to the immediate surroundings of the plants. This is known as root-zone heating and saves approximately as much energy as turning down the thermostat 5 to 10 degrees [95].

There are several common types of root-zone heating: in-floor, under-bench and under-bench hydronic. These systems are more efficient because they focus on conditioning only the necessary space. In-floor heating systems most include plastic pipes embedded in concrete or sand through which warm water is circulated. In applications using solar energy or waste heat, a flooded gravel layer under the concrete floor has been used to store as well as deliver heat. Under-bench heating using various types of tubing or plastic pipe circulate low temperature water [172].

In floor radiant heat has been used in greenhouses in combination with fossil-fuel-fired boilers, solar collectors, or waste heat sources. Roberts et al. [173] conducted an experiment to test the feasibility of in-floor heating utilizing plastic pipes covered by 7 centimeters of porous concrete. To accommodate for the large thermal inertia of floor heating, [174] tested the effectiveness of feedforward logic, by creating a prediction model and then an experiment using a controlled-environment chamber. Other models that attempt to optimize in-floor heating systems include those by Puri [175,176].

2.9 Renewable Energy Integration for Greenhouse Application

2.9.1 Photovoltaics

Photovoltaic energy generation applied to greenhouses offers another opportunity to reduce energy consumption. Many studies have been conducted regarding the optimal roof area that can be covered with PV. Specialty technology such as transparent PV and Fresnel lens have also been researched. Many studies include an economic component to their study to determine whether incorporating photovoltaic solar is feasible.

A recent study by Li et al. [177] looked at the economic and social performance of integrated photovoltaic, agricultural greenhouses systems in China. In their case study of five greenhouses, they found that the annual return on investment varies from about 9% to 20% with a discounted payback period of 4 to 8 years depending on the different crops produced in PV greenhouses.

There is a delicate balance between providing enough photovoltaic area to produce sufficient electricity and over-shading the plants. Cossu et al. [178] studied solar radiation distribution inside a greenhouse with south-oriented photovoltaic roof and the effects that this had on crop productivity. The experimental greenhouse roof was fifty percent covered with solar panels. This resulted in an eighty-four percent reduction in light beneath the panels and a 46 percent reduction beneath the plastic cover for an average reduction of sixty-four percent. This study concluded by providing suggestions for a better agronomic sustainable greenhouse. Similarly, Yano et al. [179] investigated electrical production and solar penetration for two geometric arrangements of photovoltaic arrays on a greenhouse roof. Both configurations of solar panels covered 12.9 percent of the roof area. This study found that a checker board arrangement of PV panels produced a more even distribution of light and only slightly less electricity making it the preferable configuration over a straight- line arrangement.

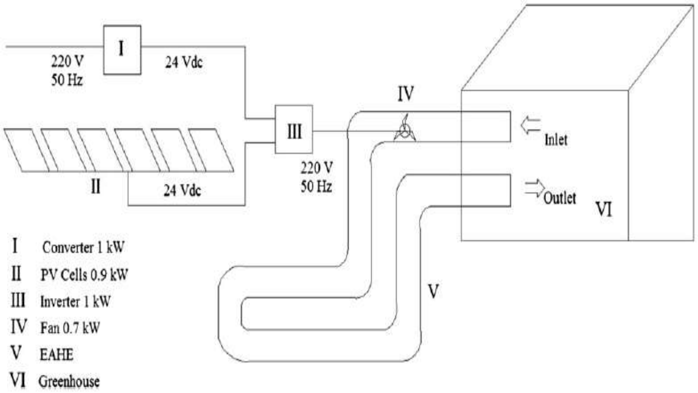


Figure 11: Schematic of the experimental system containing PV and EAHA (Yildiz et al., 2012)

Yildiz et al. [180] created An experimental system to test the performance of a solar photovoltaic assisted earth-to-air heat exchanger (underground air tunnel) used for greenhouse cooling. Figure 8 is a schematic of the experimental system containing PV and EAHA. This study found that 34.55% of this energy demand was provided from photovoltaic cells while 65.45% of the electricity energy demand was provided by the grid.

A study by Ureña-Sánchez et al. [181] examined the effect of flexible solar panels, mounted on top of a greenhouse for electricity production, on yield and fruit quality of tomatoes. They found that solar panels covering 9.8 % roof area of the greenhouse did not affect yield or price of tomatoes despite the negative effect on fruit size and color.

Carlini et al. [182] used a TRNSYS simulation to compare the effects of PV panels on a greenhouse in several locations in Italy; Turin, Rome and Ragusa. The results show energy savings for both heating and cooling with the addition of PV panels. (TRNSYS section also)

Also using simulation, Castellano [183] studied the effect of different configuration of PV panels on the covering of greenhouses. In his study, He used an Autodesk Ecotect Analysis. The analysis was run for three PV to clear panel ratios and three different PV configurations.

Hussain et al. [184] compared the thermal performance characteristics of linear and spot Fresnel lens solar collectors for heating application in Chuncheon, South Korea. The two systems, with similar storage capacities and surface areas, were tested under the same weather and operating conditions. Both systems were equipped with a dual-axis solar tracker for tracking the sun position and a circulating pump for forced convective heat transfer. Results indicate that the spot Fresnel lens performed about 7-12 % higher than the linear lens.

One of the major challenges associated with photovoltaic installations on greenhouses is the adverse effects of shading. Semi-transparent modules have been investigated for greenhouse application. Cossu et al. [185] studied a prototype semi-transparent PV module (STM) integrated on various aspects of greenhouse roofs. The modules were comprised of 4800 spherical micro-cells sandwiched between glass plates. The opaque cells covered approximately 2.3% of roof but blocked 9.7% of the light when including the metallic conductors. This study found that more traditional CPMs were 50 times more efficient than the STM system. This means that only 2% of the greenhouse structure would need to be covered by opaque CPM panels in order to produce the same amount of energy as an entire greenhouse covered in semi-transparent modules. With this prototype technology the STMs do not seem practical however, STMs had the advantage of equivalent energy production with any incident angle of sun due to their spherical nature making them suitable for alternate orientations of roofs or walls. They may also be practical for greenhouses that require shading or light diffusion regardless of the PV generation since the semi-transparent modules provide a slight and uniform light reduction over the entire space.

Lamnatou and Chemisana [186] discussed solar radiation manipulations and their role in greenhouse claddings. They looked at literature regarding passive and active Fresnel lenses, Near-infrared and Ultraviolet blocking materials. In a second related review, they looked at claddings that modify Red/Far-red, Blue/Red, Blue/Far-red ratios; fluorescence solar concentrators; passive optical means; desalination roofs; anti-condensation materials; covers which diffuse sun light and others [187].

2.9.2 Photovoltaics and Solar-Thermal

Nayak and Tiwari [188] created a simplified model to evaluate the performance of a photovoltaic coupled with thermal system for a greenhouse located at IIT Delhi, India. In a continuation of this study an earth air heat exchanger was added to the model and a theoretical energy and exergy analysis was conducted [189]. Final different climatic conditions were tested to determine where the system performed best and a comparison of various energy metrics, such as energy payback time, electricity production factor and life cycle conversion efficiency of the system was considering [190].

Sonneveld et al. [191] Studied the performance of a greenhouse with electrical generation using a hybrid photovoltaic cell, thermal collector module combined with reflection of near infrared radiation. greenhouse with linear Fresnel lenses in the cover performing as a concentrated photovoltaic (CPV) system is presented. The CPV system retains all direct solar radiation, while diffuse solar radiation passes through and enters the greenhouse. Fresnel lenses diffuse the light and reduce direct radiation entering the greenhouse by up to 77%. This drastically reduces the need for cooling in the summer. The direct radiation is concentrated by a factor of 25 on a photovoltaic/thermal (PV/T) module and converted to electrical and thermal (hot water) energy. The PV/T module is kept in position by a tracking system based on two electric motors and steel cables. The results also show a promising system for the lighting and temperature control of a greenhouse system, providing simultaneous electricity and heat. It is shown that the energy contribution is sufficient to cover the heating demand. Previous studies were conducted to prove the feasibility of the system [192], [193], [194].

Ganguly et al. [195] performed modeling and analysis of a greenhouse power system consisting of solar photovoltaic panels, electrolyzer bank and Polymer Electrolyte Membrane (PEM) fuel cell stacks. After meeting the requirements of the greenhouse, excess electrical energy generated by the photovoltaic array is supplied to and electolyzer bank to generate hydrogen gas. The gas is consumed by the PEM fuel call to supply power during energy deficit hours. They found that 51 solar photovoltaic modules each of 75W coupled with a 3.3kW electrolyzer and 2 PEM fuel cell stacks, each of 480 W, can support the energy requirement of a 90m2 floriculture greenhouse with fan-pad ventilated system.

2.10 Energy Efficiency in Greenhouse Operation

In northern latitudes and extreme climates, the cost of heating and cooling greenhouses can be 70 to 85 percent of the total operation cost [96]. Even in warmer areas such as the southwestern US these costs can amount to 50 percent of the total. To reduce this energy consumption, efficient mechanical systems are a crucial component of design, but there are also operational measures that can drastically effect greenhouse efficiency. Temperature set points, relative humidity levels and CO_2 concentrations present themselves differently when considering the needs of plants rather than human comfort. This section outlines energy efficiency considerations for greenhouse operation. It covers the unique parameters of environmental control and then discusses how these parameters might be altered to reduce energy consumption while maintain yield. Additionally, sensor networks and control algorithms can be used to optimize operation and improve efficiency.

2.10.1 Energy Saving Measures

Temperature, relative humidity and carbon dioxide concentrations are interconnected components of the environment that have a significant effect on the growth and health of plants. These three elements can be dynamical controlled to improve environmental and economic efficiency. Energy saving measure include implementation of temperature regimes, reduced relative humidity using ventilation with outside air, condensation on a cold surface, and absorption by a hygroscopic material and CO_2 supplementation during critical times of the day. With each of these parameters, there is a balance between economic viability and increased yield.

Since the environment is largely based on the composition of air entering and leaving the greenhouse environment it is important to evaluate the rate of infiltration to properly manage the space. This can be done by measuring air exchange capacity (fan cubic feet per minute), air distribution (inlet air speed) and static pressure difference [196]. Ventilation is a system where these three features work together for efficient performance. Sufficiently fast inlet air speeds of 700 to 1000 fpm encourage good air mixing and distribution within the greenhouse [196]. An anemometer is used to measure air speed, with various types such as hot wire, vane, and velocity pressure available for specific applications. Airflow visualization can help to identify problem areas and guide changes in management, ventilation system operation, or equipment [196]. This is an important part of temperature control because it indicates if mechanical systems are operating at their full potential.

Temperature Regimes

Temperature regimes are temperature schedules that are designed for a space over a period of time. This can be as simple as a thermostat with a constant fixed temperature however, these can be manipulated to increase the efficiency of a greenhouse without negatively effecting the health of plants in several ways. Here is discussed the specific requirements of plants and how this allows temperature regimes in the greenhouse to be treated very differently than a typical building. The concept of temperature integration as an energy saving measure is introduced and several variations are explored though existing literature.

Temperature is one of the most important factors in the health and morphology of plants. Each type of plant, at each phase of its growth, has a different ideal environmental temperature. Fortunately, the response of plants to temperature is mostly predictable and they each have a temperature range over which there is an almost linear increase growth response [144]. What's more, it is widely accepted that, within a range, hourly variations in temperature does not drastically effect plant growth if a consistent daily average temperature is maintained. The range is determined on the high end by temperatures at which damage will occur and on the low end by temperatures at which no growth will occur [197]. With day and nighttime set point temperatures within in this range, a simulated diurnal cycle can be used to manipulate growth. As a general rule, daytime set points can be 8 to 10 degrees warmer then night set points [144]. This concept is referred to as temperature integration (TI) and aims to maintain the same average temperature as optimal growth conditions while minimizing heating demand [198].

Much research has gone into the idea of temperature integration. Van Henten and Bontsema [199] researched optimization of open-loop temperature control in greenhouses to minimize energy consumption by maintaining an average temperature over one day instead of a rigid pre-defined set-point. Similarly, Körner and Challa [200] aimed was to improve the temperature integration concept by introducing dynamic temperature constraints. Later Their concepts were utilized in a combined greenhouse climate and control model by Körner et al. [201] to study energy consumption in year-round cut chrysanthemum greenhouse. Two techniques for temperature integration were tested and their energy saving were calculated. The first method was temperature integration within 24 h using the margin between heating and ventilation temperature as control. The second temperature integration regime was restricted within 24 h by a set point for negative temperature difference between average day and average night temperature to attain a temperature regime for stem length control. Energy consumption was reduced by both regimes compared to a standard commercial practice. This study was followed by another which used a similar climate and control model to create a decision support tool with the purpose of determining which week of the year to use which climate control regime for the optimal gain of sustainability and plant quality [202].

One study conducted on marijuana, rose, and sweet pepper plants experimented with temperature variation. Integrated control on a 24-h basis with band widths of up to 8°C was compared with a traditional control. The effects on energy consumption, plant growth and development were analyzed over the course of a year. The study concluded that energy savings of 8% could be achieved at a band width of 4°C, while at a band width of 8°C, the savings was 18%. Band widths of 4°C and less did not show any effects of the integration control on yield and quality [203].

These temperature "bands" allow for both hotter and cooler temperatures but, the bands do not guarantee that the average temperature stays the same. If temperatures are hotter during the day they must be balanced by cooler temperatures at night. An example of this was demonstrated by Pressman et al. Pressman et al, 2006 in his study on the effect of day and night time temperature variations on pepper plant growth. He found that plants exposed to low night time temperatures exhibited symptoms such as retarded growth, reduced leaf number, and deformed fruit. These negative symptoms could be avoided by closing the greenhouse during the day, exposing the peppers to hotter daytime temperatures. This reduced the need for both night time heating and daytime cooling [204].

Another study [205] adapted a temperature control algorithm to fit local needs and climatic conditions for a plastic greenhouse cultivated with gerbera. The algorithm allowed indoor temperatures to cycle in phase with the external temperature by means of a solar clock instead of a computer clock and the desired temperature was modulated as a function of global radiation. Hourly and daily corrections maintained the short and long term temperature averages within the desired levels. It was found that, using this control algorithm energy saving of 16% over the course of two years were achieved without any reduction in yield. This was primarily achieved though elevated nightly temperature set point during cold and windy weather and reduced set point during warmer and calm conditions.

It is important to note that the optimum temperature for a crop may not be the temperature that produces the highest yield. The set point temperature is often the temperature at which the cost of heating and the yield are balanced to maximize economic gain [197].Temperature can also be used to control the plant form. Transitory or constantly high temperatures cause an array of morpho-anatomical, physiological and biochemical changes in plants, which affect plant growth and development [206]. Over the long term this can lead to dramatic reduction in economic yield but, if used conscientiously at strategic intervals could be used as a sustainable alternative to chemical growth regulators [197].

Humidity Management

Humidity is the second major criteria for environmental control and is closely tied to temperature control. The negative effects of excessive humidity include reduced transpiration and ideal environment for the spread of fungal infection and other diseases [197]. There are three primary methods used to control humidity: ventilation with outside air, condensation on a cold surface, and absorption by a hygroscopic material [207]. Unfortunately, temperature integration can result in fluctuating and often high relative humidity (RH) levels in modern, highly insulated greenhouses with low infiltration [208]. Air movement and knowledge of how humidity reacts to temperature can help to prevent condensation on leaves and improve the homogeneity of the air.

A crucial component of humidity and moisture control is air movement. This aids evaporation and helps to prevent stratification. Basket fans are the most efficient and common technology used to move air [95]. They are mounted at about a quarter of the length of the greenhouse and directed in opposite directions to create circular air movement [95]. Other common types include Paddle and Jet fans. All ventilation fans require a substantial amount of electricity but, are crucial in regulating humidity and temperature. As such, it is important to select fans carefully based on their efficiency and their required function. The BESS Lab of the University of Illinois performs tests on the efficiency of ventilation fans to help customers make energy efficient decisions (BESS Laboratory Website).

Campen [207] studied the economic efficiency of the three commonly used methods of dehumidification. For condensation on a cold surface he concluded that less than half of the total heat transfer is related to the heat released during condensation. The rest is sensible heat removed from the greenhouse air. This sensible heat needs to be returned through heating which consumes more energy than necessary for the dehumidification only. Using a hygroscopic material to dehumidify a greenhouse was found to be excessively expensive and impractical. Based on this he concluded that ventilation with outside air and heat recovery is the most economical, practical, and energy-saving method.

Jolliet [209] created a model to predict humidity and transpiration directly as a function of the outside climate, with the objective of developing optimal control strategies for humidity in greenhouses. This model was straightforward but, included the processes of transpiration, condensation, ventilation and humidification or dehumidification.

A process-based humidity control concept was developed by Körner and Challa [208] for cut chrysanthemum crop cultivated with temperature integration and regular temperature control. RH control set points were generated as function of underlying processes. Greenhouse performance with this humidity regime and different temperature regimes were simulated with respect to greenhouse climate, energy consumption and photosynthesis. Compared with a fixed 80% RH set point, annual energy consumption of a year-round greenhouse could be reduced by 18% for TI with ±2 °C temperature bandwidth as well as for regular temperature control. For separate 12 week cultivations with planting date 1 March, energy saving could increase up to 27 or 23% for TI and regular temperature control, respectively.

When considering humidity, it is important to predict the interaction between the dehumidification technique and the temperature control system. While Campen [207] found that removal of moisture through condensation worked against the temperature control system, in warmer climates where cooling of the air is needed rather than heating, this system could be much more efficient.

Carbon Dioxide Control

CO_2 enrichment of the greenhouse atmosphere above external levels has been found to increase growth rates and improve the health of plants [197]. Most plants show a net photosynthesis increases as CO_2 levels increase from 340–1,000 ppm (parts per million) [210]. CO_2 is generally found at about 400 ppm in the outdoor air however, it is often the case that levels of CO_2 within the greenhouse are lower than outside air due to photosynthesis and the uptake of CO_2 by plants [211]. In these cases, the benefit of CO_2 enrichment depends on the increase in yield and the improvement in crop quality as well as the cost of enrichment. Efficiency of the greenhouse system can be increased by thoughtfully sourcing CO_2 and utilizing it when it can be most effective.

Collecting CO_2 from a sustainable source is a key component system efficiency. There are several ways to provide CO_2 to the greenhouse environment [212]. The oldest and most common strategy is a propane burner which delivers CO_2 directly to the space [213]. Unfortunately, this method is not environmentally friendly since it requires the combustion of fuel solely for the purpose of CO_2 production. A more efficient method is to capture pure CO_2 from industrial processes and store it in a tank for regulated use [214]. However, this method can be expensive and difficult to manage. CO_2 can also be extracted from flue gases, fossil fuel furnaces and biomass or biogas furnaces [215–217]. Many studies [120,218,219] have contributed to make the process more feasible and reduce costs. Of all of these options there is no perfect solution and it is still difficult to procure pure CO_2. As a result, research as also gone towards determining the most effective use of CO_2 for plant growth.

Kläring et al. [220] studied CO_2 supply strategies for efficient use of CO_2 and maximum yield. They found an increase in yield of about 35% in a greenhouse supplied with CO_2 compared to the unsupplied standard. The differences between supplied and not supplied greenhouses in CO_2 concentration and photosynthesis, and thus the CO_2-supply efficiency, were maximal at moderate radiation and decreased with increasing outside air temperature due to required ventilation at high radiation and high outside air temperature. This indicates that the most efficient use of CO_2 is to deliver it to the greenhouse during the morning and late afternoon when the sun and internal temperatures are less intense.

The level of CO_2 enrichment and its control is closely tied to both temperature and humidity regulation. It is important that these three components are jointly considered so that the chosen systems work together rather than in opposition of each other.

2.10.2 Sensor Networks

Monitoring the greenhouse environment is an important part of making efficiency-conscious system operation decisions. However, due to the complex nature of the greenhouse environment, control of the greenhouse climate is a difficult task. Greenhouse climates are affected by many interactions between various key parameters and are difficult to model mathematically [221]. There are ongoing studies on monitoring environmental parameters such as CO_2 and the effect of CO_2 deprivation on yield [220], soil evaluation [222][223], ventilation rate [224], estimation of light interception by plants [225], and amount of solar energy entering a plant canopy.

Monitoring is most widely done through sensors and control algorithms that consider the key parameters for the greenhouse's success. One strategy for determining the effectiveness of the greenhouse environment for plant growth is to monitor the status of the plants directly. This allows growers to determine whether the conditions within the greenhouse are providing the resources needed for the plants to flourish. It is generally more difficult to monitor the plants directly because of the potentially large variation in health from plant to plant. Sensors are generally placed in only a limited number of locations which can reduce the accuracy of the reading.

Plant status is directly measured in several ways. Variation of stem diameter in tomatoes plants can be measured to indicate water stress [226]. Similarly, Vermeulen [227] conducted an experiment that measured sap flow rate, stem diameter and leaf temperature as a result of drought stress. They found that any of the three related symptoms could be used to predict when the plants were experience water shortages

Another developing technology is the measure of volatile organic compounds produced with health or metabolic changes in the plants. Jansen et al. [228] conducted an experiment to examine plant emissions of VOCs of damaged plants compared to a baseline. He found that the most dominant compounds for baseline emission were the monoterpenes β-phellandrene, 2-carene, limonene, α-phellandrene and α-pinene. Directly after damage, these compounds showed an increase of up to 100 times compared to baseline level emission. The study shows that there is potential for this type of sensing, however, more research needs to be done to determine if pests or pathogens will have the same effect.

One such parameter essential to plant growth is light interception. Janssen et al. [225] proposes a way of estimating light interception in a greenhouse using two sensors, one pointing directly upward, and the other directly downward. These sensors measure incoming light and reflected light, respectively.

The paper concludes that with application of various data filters, the data gives a good estimate of reflection ratio, which could then be used to calculate light interception or leaf area index.

An even more complex system was developed to measure the greenhouse climate. Baek et al. [229] developed a Greenhouse Control System (GCS) to take into account environmental and crop growth parameters. Sensor measurements of environmental parameters (inside, outside, and soil) and crop growth parameters (predicted) are gathered and stored in the Greenhouse Information Storage (GIS). Information is then fed to the Greenhouse Control Agent, and various controls are adjusted, changing the greenhouse environmental parameters, and thus the crop growth parameters.

Many studies make use of Wireless Sensor Networks to achieve the goals of greenhouse climate. Wireless Sensor Networks (WSN) are becoming increasingly applicable to the agricultural industry as they have the ability to monitor certain parameters key to a crop's growth or a greenhouse's climate. WSNs typically consist of nodes (which include a processor), memory, sensors, wireless or Zigbee radio communication, battery, and a base station [93]. The networks can provide real-time monitoring of key parameters, allowing researchers to continuously collect measurements. Liu et al. [230] developed a wireless sensor network where they measured temperature, light, and soil temperature. The system contained two parts: the sensor network and the remote management center. The two parts were connected through a GSM (global system for mobile communication) module. The system uses Short Message Service communication to transfer information to the management center, which worked both efficiently and economically for data transmission. In another study, a WSN, called A2S was developed and tested [231]. A2S consists of WSNs, gateways, and a management sub-system. Two nodes were developed: A-node, which collects data of the climate within the greenhouse, and C-node, which controls the illumination within the greenhouse with melons. The sink node takes data from the A-nodes and sends commands through the A- and C-nodes to control the environment. Finally, the node sensing data is stored in a server, which can then be accessed by researchers or farmers.

2.10.3 Control Algorithms and Optimization

Generally, sensor networks and control algorithms work together to control greenhouse climate. There are many methods for controlling greenhouse climate, some newer and evolving, as presented by López-Cruz et al. [221]. In all cases measured values from the environment are used to make decisions regarding the mechanical action. The potential to improve this process exists both in the method of measuring these values and in the decision-making process. This section expands on a few control strategies, or decision making techniques that have been applied to the greenhouse environment.

Proportional-Integral-Derivative control (PID)

Proportional-Integral-Derivative (PID) control is commonly used in industrial and greenhouse control. A PID controller continuously calculates the difference between the desired set point and the measured variable. A correction is then applied based on the proportional (P), integral (I), and derivative (D) of the difference or "error value". The proportional accounts for the current value of the error, the integral accounts for past values of error, and derivative accounts for future values of error based on the rate of change. This relatively simple system is broadly applicable because it relies only on measured values and not on knowledge of the underlying system however, this also limits its capabilities and makes it susceptible to delays and errors [232].

Model Predictive Control (MPC)

Model predictive control solves some of the issued experienced by PID systems by predicting future events and taking control action accordingly. To achieve this a dynamic model of the system process is required. This allows the MPC to optimize a finite time-horizon [233]. While this control method can be very efficient if all goes as planned, it is susceptible to unexpected events that render the fixed control choices obsolete.

Many studies have applied MPC to the greenhouse environment. El Ghoumari et al. [234] compared a MPC scheme for greenhouse temperature regulation with an adaptive PID controller. The MPC algorithm used in their study takes in account the constraints in both manipulated and controlled variables using an on-line linearization with a very low computational burden.

Van Straten et al. [235] performed a review of control strategies on which they based the design for an optimization system. In their system, the farmer can specify the set points and constraints for the greenhouse climate while a model-based predictor calculates the effect of these set points/constraints on the crops, and energy.

Aaslyng et al. [236] and Aaslyng et al. [237] developed mathematical model-based greenhouse climate control system – IntelliGrow - to decrease energy consumption while maintaining or increasing plant production. The mathematical model can estimate irradiance absorption, leaf photosynthesis, and respiration. Based on the climate conditions, the control system calculates optimal set points and communicate with environmental control computers (ECC) through BipsArch.

Piñón et al. [238] combined the advantages of a standard linear Model Predictive Control (MPC) with Feedback Linearization (FL) and applied the resulting control scheme to the greenhouse environment. The greenhouse in this study was considered a non-linear Single-Input–Single-Output process and subject to strong external disturbances. Piñón et al. [238] also discusses an alternative implementation to reduce optimization problems that can occur as a result of the methodology used for solving the MPC+ FL approaches. Two control techniques are compared, namely MPC+ FL and Non-linear Model Predictive Control (NLMPC).

Blasco et al. [239] explored MPC as an alternative to classical climate control. Their control strategy is based on two fundamental elements: an accurate non-linear model and a model-based predictive control (MBPC) that incorporates energy and water consumption. Genetic algorithms play a key role as solution functions are non-convex with local minima. Results for a plastic greenhouse with arched roofs in the Mediterranean area indicate significant a reduction in energy and water use.

Although they did not specifically use an MPC algorithm, Chalabi et al. [240] predicted optimal heating set points based on the weather forecast supplied by the meteorological office. The control program analyzed the weather forecast and then communicated heating set points with the greenhouse computer system.

Receding Horizon Optimal Control (RHOC)

Receding Horizon Optimal Control attempts to improve on MPC by addressing the idea of a “receding horizon”. In this method only the first step of the resulting optimal control in implemented and the measured state is used in the iterative process to predict the “future” state [241]. Tap et al. [242] tested the applicability of a RHOC algorithm in a greenhouse to optimize climate control, which was found feasible. Later on, Van Straten et al. [243] separated long-term and short-term optimizations to create an optimal control algorithm, and used a receding horizon optimal controller. The team concluded that 1) RHOC can be used to optimize the short-term economic control, 2) that using an RHOC for short-term control is robust, 3) that with the two time scales, seasonal optimization can be done separately to ensure information is provided to the short-term optimal control, and 4) that short-term controllers cannot truly be optimal if the long-term behavior of the crop isn't taken into account.

Adaptive Control

In contrast to RHOC and MPC, adaptive control is used for a system in which parameters vary or are initially uncertain [244]. This control type seeks to deal with the uncertainties within a greenhouse system by using multirate-output controllers [221]. Zeng et al. [245] combined proportional-integral-derivative controllers and a Radial Basis Function (RBF) network to control greenhouse climate. The RBF was used to tune and identify PID gain parameters. The control system was validated through simulations and the team concluded that the strategy had good adaptability and robustness. Real-time online control of MIMO systems is also attainable and the control strategy can be applied to a greenhouse system.

Arvanitis et al. [246] proposed a new adaptive technique for the control of temperature in a greenhouse where parameters vary with operating conditions. The proposed adaptive controllers are derived by solving either the pole-placement or the linear quadratic regulation (LQR) problem and use multi-rate controllers in which the greenhouse temperature is sampled many times over a fundamental sampling period. Simulation indicate the effectiveness of the proposed scheme.

Feedback and Feedforward Control

A feedforward is a term which describes an element within a control system that passes a signal from a source to a load elsewhere in its external environment. Feedbackward signals in reverse from the external environment to address how a command will affect the load and how the load may vary. Feedback and feedforward loops are used to minimize control error within the system, and are designed for real-time applications to linear and non-linear systems. Pasgianos et al. [247] presented a feedback-feedforward strategy for controlling a greenhouse's complex climate. The strategy decouples a nonlinear and coupled system to meet the climate demands of the greenhouse. The method, after tuning, accurately tracks setpoints and reduces stability issues.

Multiobjective Control

The goal of multiobjective optimization is to minimize all aspects of the objective vector. Multiobjective optimization has been used to optimize and control parameters within a greenhouse climate López-Cruz et al. [221]. Zhang [248] applied a multiobjective optimization immune algorithm within a greenhouse climate. Additionally, Hu [249] used evolutionary algorithms to create multi-objective optimization control in a greenhouse.

Fuzzy Control

Fuzzy logic is a mathematical system which analyzes variables that take on continuous values between 0 and 1. This is in contrast with digital logic which operates on discrete values of either 0 or 1. Fuzzy logic has an advantage over digital logic in that it can be cast in terms more understandable to a human operator. This makes it easier to mechanize tasks that are already successfully performed by humans [250]. This is a practical alternative for the design of a great variety of control applications. Xu et al. [251] designed a fuzzy control based system for greenhouses that controls CO_2 concentration. The control system, using fuzzy logic and a photosynthesis mechanism (based on light and temperature), can adjust the CO_2 concentrations to appropriate levels with better accuracy. Lafont and Balmat [252] created a basic and an optimized fuzzy controller and evaluated the two. The optimized fuzzy controller had many advantages over the basic fuzzy controller.

Salgado and Cunha [253] developed and tested a new fuzzy modelling technique that automatically organizes the sets of fuzzy IF–THEN rules in a Hierarchical Collaborative Structure. This organizational structure makes the fuzzy model interpretable like a physical model. The new methodology was tested by splitting the inside greenhouse air temperature and humidity flat fuzzy models into fuzzy sub-models, which have similar counterpart on the physical sub-models.

Castañeda-Miranda et al. [254] developed an intelligent climate control system that uses a fuzzy controller, based on a field programmable gate array. The proposed system can unload low-level tasks such as monitoring of climate variables and operation of actuators from the main control system in order to leave to the main controller high-level tasks as plant monitoring and irrigation system control, which require high computational power.

Other research on fuzzy control for greenhouse application has been conducted by Trabelsi et al. [255] and Lafont and Balmat [252].

Neural Control

Neural controls and networks are some of the most complicated forms of control and thus have some of the greatest potential. These computing systems are made up of highly connected processing elements which respond dynamically to external inputs. Neural networks are typically organized in layers of interconnected nodes which contain a simple activation functions. Patterns are presented to the network via an input layer which presents patterns to the network and signals deeper layers where processing is done via a system of weighted connections. These deeper layers link to an output layer where the command is generated. Fourati and Chrourou [256] used an Elman neural network to mimic the greenhouse's complex climate. The multilayer feedforward neural network has been tuned to mimic the inverse dynamics of the greenhouse and was used as a nonlinear controller with feedback to tell the system which actions to take. Simulations of the system show that the strategy works, but can be improved. In a later study they attempted to improve control using generalized and specialized learning [257]. Many other studies on the neural networks for greenhouse application have been conducted [258–265].

Other Algorithms

Coelho et al. [266] utilized a particle swarm optimization algorithm as a new method to design a model-based predictive greenhouse air temperature controller subject to restrictions. Its performance is compared with those obtained through genetic and sequential quadratic programming algorithms to solve the constrained optimization air temperature control problem. The results indicate a better efficiency of the particle swarm optimization algorithm as compared with the efficiencies obtained with a genetic algorithm and a sequential quadratic programming method.

Setiawan et al. [267] compared Pseudo-Derivative-Feedback (PDF) control to PI control through simulation using an approximated dynamic system thermal model of the greenhouse. Results indicate that PDF control has a better load handling capability than PI control. PDF control particularly out preformed PI for systems without time delay but was also significantly better for systems with time delay. The algorithm was then tested on a greenhouse section and showed satisfactory results.

2.11 Simulation

Modeling of greenhouses began more than fifty years ago and has continued to grow in complexity and accuracy. Although simplification is necessary to create an applicable model, there are "parameters that must be considered to achieve an accurate model. For a greenhouse these parameters include, but are not limited to plant carbon balance, photosynthesis, respiration, and allometry" [268]. An increase of greenhouse exploration and innovation occurred in the late 1970s when many studies sought improvements in commercial greenhouses due to the oil crises [85]. One of the most notable early models was created by Walker [269]. This model used thermal inputs from solar radiation, respiration and equipment and balanced these with losses from convection, radiation, photosynthesis, conduction and ventilation. Later, Price and Peart [270] combined Walker's model [269] and a multiple reservoir model to study the use of waste heat. Although not specifically related to greenhouses, Degelman [128] created a notable weather simulation which calculated temperature, dew point, solar insolation, and wind velocity every hour for a year. His model was later integrated into many studies and greenhouse models. The increased computing power and speed of computers has allowed for a new generation of simulation and processing tools that have been applied to greenhouse technology.

Although the technology needed to model the greenhouse environment now exists, much of the work that has been done within this field is commercial and remains proprietary. This conclusion was drawn based on a series of informal interviews conducted at the 2016 Canadian Greenhouse Conference held on October 5-6 in Niagara, Canada. Academic institutions, researchers and commercial growers from around the world were represented at this conference. Most of research presented at the conference focused on the improvement of plant growth through individual aspects of the greenhouse environment/plant interaction such as nutrient delivery systems or optimal lighting. These experiment-based studies act on the principal of isolating variables and a complex model weighing many variables is unnecessary. On the other hand, commercial companies that design greenhouses are forced to look at the system, as a whole, on a daily basis. As a result, each company has created its own mathematical representation of the greenhouse environment to facilitate design. A literature analysis supports the conclusion drawn from informal interviews that the conference. Very little academic research has be dedicated towards modeling of the complete greenhouse environment. Of the research that has been conducted, the most notable are summarized below.

2.11.1 ENVOLVER

Chinese et al. [271] created simulation models with static energy balance equations to determine heating and cooling requirements. The authors' study serves to optimize a greenhouse heating system and the economic costs of the system by exploring the feasibility of using a waste-to-energy plant for greenhouse heating. In this study, a hot-water pipeline system was adopted and simulated with ENVOLVER, a genetic algorithm based solver. The models created can be used to observe the technical and economic optimization of systems with waste heat, and authors suggest that this approach to modeling could be applied to other renewable energy sources as ideas are developed.

2.11.2 MATLAB

MATLAB has been used to solve heat and mass transfer equations for modeling dynamics of greenhouses. Menghini et al. [272] used MATLAB in their evaluation of a solar cooling plant applied for greenhouse thermal control. Ghosal et al. [273] modeled a greenhouse integrated with earth to air heat exchangers using MATLAB program. This model was also experimentally validated and found to be in close agreement [273]. Ahamed et al. [274] created a pseudo dynamic thermal model for simulating the heating/cooling energy requirement based on lumped estimation of heat flow parameters in greenhouses. The developed model can simulate the hourly heating/cooling requirement of greenhouses based on input information about desired indoor environment, dimension, and thermal properties of constructional materials, characteristics of selected crop, and local weather data.

Vadiee and Martin [85] built a simulation model with three sub-models. One was used to formulate the indoor climate and two were for analyzing the growing plants. This model is well-defined with a high level of detail, but has been validated only for a tree seedling greenhouse. Hill [268] used the model by Vadiee and Martin [85] as a spring board for his own model which was created as an aid to greenhouse operators concerned about energy management. His model was called GUESS (Greenhouse Use of Energy Seedling Simulator) and is a "lumped-parameter coupled dynamic simulation combining a carbon-based process model of seedling growth with a heat/mass transfer model of the greenhouse envelope". The source code for GUESS was written using MATLAB and Simulink. In a lumped parameter method, spatial variations are ignored and all internal fluxes through the control volume's boundary are assumed to have uniformed distribution. The process based model of the crop canopy allowed Hill to simultaneously assess the cost of production alongside the impacts on the health and growth of the crop, however, Hill's model is limited to a tree seedling nursery a should be modified for typical commercial greenhouses.

2.11.3 The Watergy Greenhouse Model

Speetjens et al. [83] designed the Watergy Greenhouse model to assess innovation in temperature and humidity control. The models represent a fully closed greenhouse cooled only by natural convection. The model is valid for a special case and cannot be generalized.

2.11.4 INTKAM

The INTKAM model involves many sub modules for transmitted radiation into the greenhouse and the crops respectively. Modules include photosynthesis phenomena, indoor climate condition, and yielding issues. INTKAM has been validated for different conditions in a conventional greenhouse, but not specifically for the closed greenhouse situation [80].

2.11.5 TRNSYS

TRNSYS was used to simulate the behavior of transient systems and can be applied to greenhouses through a pre-defined building subroutine in the TRNSYS standard library. Fuller et al. [275] and Hollmuller and Lachal [276] used TRNSYS in their respective studies. In their models, a new type was defined through TRNSYS called ''greenhouse.'' This type is mostly based on a pre-defined building subroutine in the TRNSYS standard library. Components are validated partially in different greenhouses. These models concentrate more on the heat exchangers which are employed in the greenhouse. Hoes at al. [84] coupled a plant/climate interaction model with TRNSYS to model closed greenhouse simulation tool.

2.11.6 Dynamic Modeling and Simulation of Greenhouses: A Web-based Application

This software's model includes climate data, a greenhouse structure database, and greenhouse crop environmental data [277]. The model was programmed in ActionScript 2.0 with an interface in Flash MX.

The user may select between available greenhouse options but, is limited by the minimal options. Climate data is currently available for four locations and mechanical systems are limited to hot air systems.

2.11.7 Computational Fluid Dynamics

Computational fluid dynamics has been used in many greenhouse studies. This simulation method is particularly beneficial for modeling air flows and ventilation effects. Fatnassi et al. [90] worked on optimization of greenhouse insect screening with Computational Fluid Dynamics, and Biosystems engineering. Sase [142] looked at air movement and climate uniformity in ventilated greenhouses and the effects of external air speed. Kacira et al. [146] investigated the effects of side vents and span numbers on wind-induced natural ventilation of a gothic multi-span greenhouse. Mistriotis et al. [147] analyzed the efficiency of greenhouse ventilation using computational fluid dynamics and studied the effect of the greenhouse length on the inside flow pattern. Reichrath and Davies [148] used a CFD to model the internal climate in Venlo type greenhouses. Villagran et al. [137] used CFD to optimize ventilation and its effect on the microclimate of a Colombian multi span greenhouse.

2.11.8 EnergyPlus

McMorrow et al. McMorrow et al. (2015) conducted parametric study on sizing a greenhouse using waste heat from a sugar plant in winter with a prestigious building simulation software—EnergyPlus. Common types of greenhouse materials and common required temperature set-points from growing tomatoes and cucumbers were set up for the simulation models. In this study, only heating and cooling loads were predicted, and no mechanical systems were defined in the study.

2.11.9 Modeling in Industry

While many studies have been conducted regarded individual scenarios, there does not appear to be much simulation within the greenhouse industry. It may because companies outsource energy modeling to consulting firms such as MRIGlobal. MRIGlobal is an independent organization that performs contract research for industry and government. MRI conducts programs in the areas of national security and defense, life sciences, energy and the environment, agriculture and food safety, and engineering and infrastructure, and has a department that is focused in greenhouse modeling and analysis.

2.12 Literature Synthesis

This literature review on greenhouse environmental control briefly covers construction, design criteria, lighting, heating and cooling systems, energy efficiency measures, renewable energy integration and greenhouse simulation. It is evident that there is extensive research on many facets of greenhouse design. However, there are still large holes in our understanding of controlled environment agriculture. This is, in part, due to the complex nature of the problem. While a traditional building has more luxury in isolating the interior from the exterior environment, greenhouses are constrained by their need to maximize natural light. This balance of light penetration and environmental isolation are vastly different for each location, crop, and desired function of the controlled environment. As a result, there are few standards for design that can accurately predict how a greenhouse will be effected by its local climate.

The review section on greenhouse construction primarily focused on greenhouse cladding, which provides the barrier between the inside environment and the exterior conditions. Different cladding types provide desired functions such as insulation or allow for ventilation while still permitting the necessary amount of solar radiation to reach the pants. Benefits and limitations of intelligent construction materials such as thermoelectric materials and latent heat storage material have been investigated and tested for new greenhouse construction however, there is plenty of room for further investigation as new material continue to emerge. The new generation of construction materials are active and responsive to the variation of weather conditions providing new opportunities for energy savings.

In response to the challenges of construction, LED lighting offers a new wealth of possibilities for greenhouse design and optimization. Among other possibilities they can light effectively between rows so that facilities do not rely solely on overhead lighting, be used to manipulate the growth of plants, and be optimized to the specific requirements of the plants so all emitted wavelengths are utilized. Because this technology is still relatively new, research still needs to be done in this area. As the demand for these more energy efficient and longer lasting lights grows, research will continue to provide more insight into their most effective use. At this point, the major limiting factor to LED lighting for greenhouse application is the relatively high upfront cost.

In the vast majority of greenhouses, basic and relatively inefficient heating and cooling systems have been implemented. Thus, there is lack of academic understanding when it comes to more complex systems. Several areas, such the effect of different material and construction methods on natural ventilation have been widely explored but, this breadth of knowledge is limited to the simplest systems. A minimal number of studies have covered the effects of renewable heating and cooling systems such as biofuel, geothermal, water and air heat pumps, and solar thermal.

Similarly, the integration of renewable energy production such as photovoltaics has been minimally studied for greenhouse application. There is some potential in this field however, it seems counterproductive as the plants are then competing with the production system for solar energy. What potential there is exists in filtering the wave lengths so that the plants receive 100 percent of their required diet of light while the energy production system collects the rest and prevents it from entering the space in the form of heat.

One of the most important aspects of greenhouse sustainability and efficiency are the use of energy efficiency measures. An energy efficiency measure is a broad term that refers to any operational process by which the greenhouse can reduce its energy consumption. This can be accomplished primarily by monitoring or predicting the greenhouse environment and controlling the mechanical systems accordingly. Temperature, relative humidity, and carbon dioxide are environmental parameters that typically need to be maintained through mechanical processes. Energy use due to temperature control can be minimized using temperature integration which allows for temperature ranges rather than strict temperature set points. There are many algorithms and control strategies that have been developed to dynamically control these parameters. However, each greenhouse offers unique challenges and there is no established “best solution”.

As research continues and greenhouse design continues to evolve, it is trending towards larger and more high tech facilities. These have a much larger upfront cost and are thus a much greater risk making is very important to accurately predict and model greenhouses before they are built. Despite the obvious need, there is no commonly used platform that supports greenhouse modeling. Many disjointed models have been created over the years but, they each have their strengths and weaknesses and are not generally comparable with one another. There is a great need for a readily available and technically accessible modeling tool that can accurately represent the full sophistication of the greenhouse environment. This would not only be beneficial to individual projects but, would also serve as platform on which research could communicate.

With growing energy and food demands, greenhouses have the potential to become a much larger industry than they are today. If designed thoughtfully with efficiency in mind, greenhouses can fill the market created by the growing trend toward local, year-round, viable, commercial scale farming. To make this feasible, we need to think about the unique characteristics of greenhouses and conduct research that aims to take advantage of the strengths such as the huge potential for thermal energy sequestration and minimizes the effect of the disadvantages.

Chapter 3 EnergyPlus Greenhouse Model Validation

Greenhouse modeling is seldom used in comparison to the modeling of a typical building. Because of this, there is no standard for the modeling of greenhouses. Many forms of greenhouse modeling have developed over the years but they are disjointed and, in most cases, the results are not comparable. This makes it difficult to coalesce knowledge into a comprehensive understanding of greenhouses. This study uses EnergyPlus to model a low-tech greenhouse on the University of Wyoming campus. Concurrently, the greenhouse was monitored for energy use, light, temperature, relative humidity and carbon dioxide. Results from the EnergyPlus simulation were then compared with the measured values to gage the ability of EnergyPlus to accurately model the greenhouse environment. This type of research is conducted with the goal of finding a commonly used, powerful software that can unify the greenhouse modeling world and create a platform on which research can build. Additionally, as the level of technology increases, the initial cost also increases. This makes it more important to accurately predict the performance of the facility.

EnergyPlus is a whole building energy simulation program used by engineers, architects, and researchers to model a buildings energy consumption for heating, cooling, ventilation, lighting and plug and process loads. This software was chosen for its ability to produce integrated, simultaneous solution of thermal zone conditions and HVAC system response without assuming that the HVAC system can meet zone loads and its consideration of radiant and convective effects that produce surface temperatures thermal comfort and condensation calculations. Most importantly for greenhouses, or other large open spaces, EnergyPlus can account for air movement between zones. This allows for perimeter or overhead zones to be examined separately to understand temperature distributions within a single space. Other beneficial features include sub-hourly, user-definable time steps, advanced fenestration models, illuminance and glare calculations, and component-based HVAC system design. EnergyPlus works with OpenStudio, a graphical applications which include the OpenStudio SketchUp Plug-in. The OpenStudio SketchUp Plug-in is an extension to Trimble’s popular SketchUp 3D modeling tool that allows geometry to be quickly created and imported to EnergyPlus. The OpenStudio Application is a fully featured graphical interface which includes envelope, loads, schedules, and HVAC.

These programs were used to simulate a small, existing greenhouse in Laramie WY. Data was collected from the greenhouse over the course of ten days from June 22nd to July 3rd. These data were compared to the simulation results to establish the ability of EnergyPlus to accurately model a controlled agricultural environment.

3.1 Data Collection

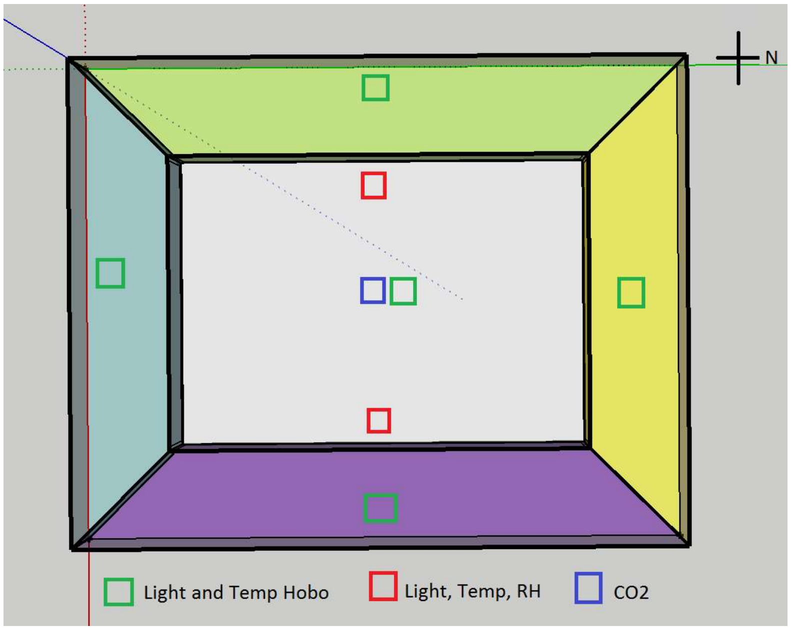


Figure 12: Zone and sensor layout of University of Wyoming greenhouse

Figure 13: Custom CO_2 sensor

Data was collected by sensors arranged throughout the greenhouse and by monitoring the energy consumption of the space using the university MetaSys data. Sensors included five Hobo meters measuring light and temperature, two Hobo meters measuring light, temperate and relative humidity and one carbon dioxide sensor. Sensors were arranged as shown in figure 11. These locations correspond to the zone break down of the space used in the EnergyPlus model and allow for comparison of individual zone temperatures. Because only two sensors measuring relative humidity and a single CO_2 sensor was available, the largest, central zone was chosen as the most likely to return values that represent and average of the space. Hobo meters were programed to collect data every fifteen minutes continuously for ten days while the CO_2 sensor collected data every 2 seconds.

The CO_2 sensor was an original combination of CO2 sensor attached to Arduino circuit board These components were housed in separate, semi-water tight containers and connected by short communication wires. Figure 13 shows the two components in their transparent containers. The CO_2 sensor was exposed to the environment by a fitted hole on the bottom of the casing. This was designed to protect the system from humidity and water damage and prevent the loss of data.

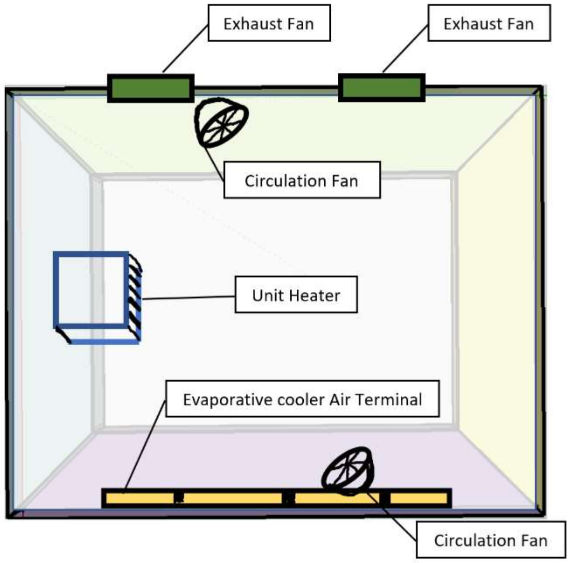


Figure 14: Mechanical system layout in the University of Wyoming greenhouse

The University of Wyoming is monitored and controlled by Johnson Controls' Metasys® Building Automation System. This is an intelligent technology system which connects HVAC, lighting, security and protection systems, enabling them to communicate on a single platform to deliver information. For monitoring the greenhouse, this meant setting up a number of points that monitor when the mechanical systems in the space are running. The location of mechanical systems is shown in figure 13. This diagram shows that Zone 1 contains all vents which distribute air from the evaporative cooler, and zone 3 contains both exhaust fans. Zones 1 and 3 contain circulation fans at head height and the unit heater is suspended above zones 4 and 5. All mechanical components in this space had simple on/off controls which allowed for a simple calculation of the total power consumption.

3.2 EnergyPlus Modeling

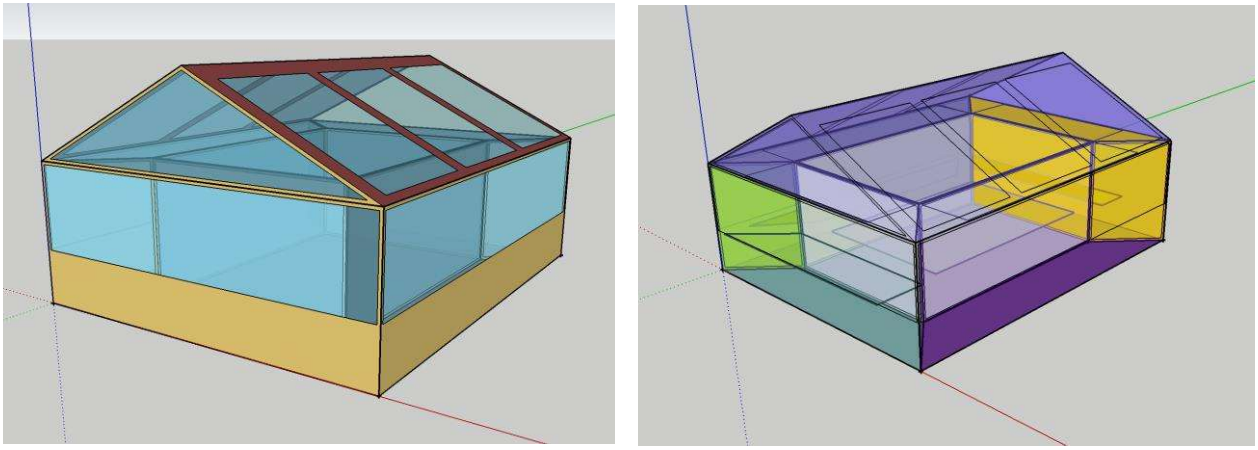


Figure 15: SketchUp geometry for EnergyPlus model

The OpenStudio plugin in SketchUp was used to create the geometry for the EnergyPlus validation model. Figure xxx shows the geometry created in SketchUp. Materials and construction correspond to the existing greenhouse. The greenhouse was split into five lower zones so that microclimates, created by locations of the mechanical systems and exterior climate exposure, could be analyzed. A sixth zone represents the unconditioned peak of the roof. Figure 14 shows the breakdown of zones and figure 15 shows the boundary conditions applied to the different surfaces. The north wall, shown in pink in figure 15, was modeled with adiabatic boundary conditions to represent the fact that the greenhouse has a conditioned adjacent space on that side.

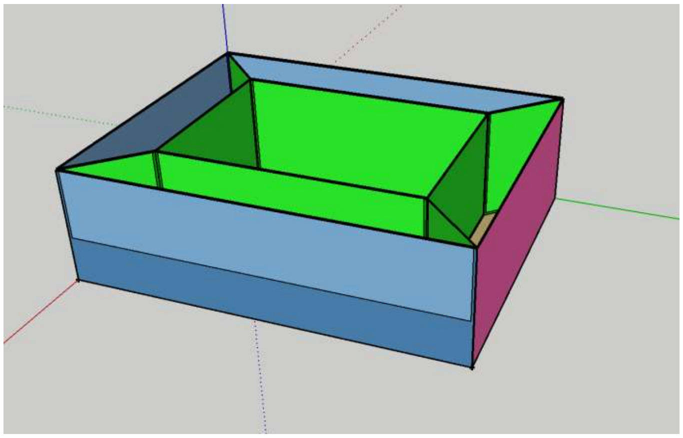


Figure 16: Boundary conditions applied through OpenStudio SketchUp plugin

To model airflow between the interior zones, a Zone mixing and cross mixing was used. The air transfer rates for this was based off of the circulation fans airflow rate of 450 cfm. This was important because the zones are small and are not individual conditioned.

Several assumption regarding material and Zone were made. These are summarized in Table 6. Assumptions associated with cladding material were based on specification for a similar material found on the market today [278]. Infiltration rate was assumed based on rates measured in leaky, old buildings using blower door tests [279]. Although the infiltration rate was assumed without supporting data from the UW greenhouses, it was found that the rate of infiltration had very insignificant effect on the results. Because of this the rough assumption was considered acceptable.

Table 6: List of Assumptions made in EnergyPlus model and their associated values

Assumption	Parameter	Value	Units
Low-Wall	Name	12IN Concrete HW	
	Roughness	MediumRough	
	Thickness	0.3	m
	Conductivity	1.7296	W/m-K
	Density	2400	kg/m3
	Specific Heat	7500	J/kg-K
	Thermal Absorptance	0.9	
	Solar Absorptance	0.65	
	Visible Absorptance	0.65	
Cladding Material	Name	Corrugated Plastic	
	Optical Data Type	SpectralAverage	
	Thickness	0.003	m
	Solar Transmittance at Normal Incidence	0.8	
	Front Side Solar Reflectance at Normal Incidence	0.08	
	Back Side Solar Reflectance at Normal Incidence	0.06	
	Visible Transmittance at Normal Incidence	0.8	
	Infrared Transmittance at Normal Incidence	0.1	
	Front Side Infrared Hemispherical Emissivity	0.9	
	Back Side Infrared Hemispherical Emissivity	0.9	
	Conductivity	0.4	W/m-K
	Dirt Correction Factor for Solar and Visible Transmit	1	
	Solar Diffusing	Yes	
Zone Air	Plant CO2 Absorption	Max=.00075	m3/s
	Infiltration Rate	7	ACH50
	Air Circulation Rate	Max=.2	m3/s
	CO2 Concentration of OA	406	ppm

Mechanical systems were represented as they appear in Figure 23 with an evaporative cooler feeding into Zone 1 and exhaust leaving through Zone 3. Heating equipment was not included in the model as there is no heating load at the time monitoring occurred. Mechanical systems were sized and configured according to specifications from the University of Wyoming greenhouse mechanical systems. Table 7 shows the systems used. For specifications and images of greenhouse mechanical units see appendix A.

Table 7: University of Wyoming greenhouse mechanical systems

Component	Company	Model Number	Capacity	Volts	Amps
Exhaust Fan	Windmaster	M689830-DC-Hort 24	5436 cfm	230	3.2
Evaporator Pump	Champion Coolers	60-120		115	1.2
Evaporator Fan	Champion Coolers	7500/8500 SD	4592 cfm	115	13.8
Unit Fan	Schaefer	VK8	450 cfm	115	1.31

There are several additional components of the greenhouse environment that are considered in a different way than in typical buildings. While high levels of CO_2 are bad for the health of humans, they are desirable for the growth of plants. Similarly, most buildings do not have large containers of standing water, dirt, and dense vegetation, all of which effect the air quality and moisture content. Several options were explored for modeling relative humidity and carbon dioxide.

In EnergyPlus relative humidity in each zone is calculated and returned but adding the output variable: zone mean relative humidity, however there is no object that represents the evaporation and respiration of interior plant. In an effort to represent this indirectly, two features of energy plus were explored. The first feature is an object Material:RoofVegetation which provides a model for green roofs. This model accounts for long wave and short wave radiative exchange within the plant canopy, plant canopy effects on convective heat transfer, evapotranspiration from the soil and plants, and heat conduction and storage in the soil layer. Unfortunately, this object has not been adapted as an interior material and was ineffective when specified as internal geometry. Similarly, an IndoorSwimmingPool object was explored as way to represent the additional thermal mass of the soil and plants and the evaporation from wet surfaces that would occur in a greenhouse or off the surface of a swimming pool. This material was found to have no effect on the relative humidity results. The material was effective as a thermal mass but this only increased the average temperature difference between actual and predicted values.

The final important component the model used in this study, was the weather file data. EnergyPlus uses weather data in the form of location specific EWP files to inform the simulation. An original EWP file for Laramie WY containing weather data for 2002 was updated to correlate the model with the weather over the monitoring period. The data for June 22, 2017 to July 3, 2017 was retrieved from NOAA's department National Centers for Environmental Information (NCEI). The NCEI collects and provides public access to climate and historical weather data and information. From this database, hourly temperature, dew point, relative humidity, wind speed and wind direction for Laramie Wyoming were gathered. This data was inserted into the original weather file to create an accurate simulation over the monitoring period.

3.3 Results

Data from the greenhouse was compared with results from the simulation in several ways. Zone temperatures were compared directly, the averages of all zone temperatures were compared and the temperature variation between the zones in the real and the zones in the theoretical greenhouse were compared. Relative Humidity was treated in a similar fashion although this parameter was limited by the small number of sensors. Finally, the energy consumption of the facility was estimated and compared to the predicted energy consumption.

The HOBO meters returned data on 15 min intervals from their specific location in the greenhouse over the time period of June 22, 6:00 PM to July 3, 11:30 AM. This data was combined using MatLab into hourly averages that were then compared with the simulation results.

3.3.1 Temperature

Despite a pre-experiment calibration, the temperature data indicated that HOBO meters were not accurately measuring temperature. The sensors indicated that temperatures within the greenhouse climbed as high as 56 degrees Celsius in some zones. At these temperatures many of the plants would have wilted or died. To discover where the error occurred, and attempt to correct the data, the sensor went through a post experiment calibration process. After calibration, the temperatures more closely resembled those returned by the EnergyPlus model, but there was still a margin of error. The model was particularly inaccurate during mid-day and late evening.

Calibration

A high accuracy sensor was used to gage the error of the HOBO sensors. Based on cooling set-point temperatures and reasonable margins of error, it was predicted that the HOBO meters were inaccurate when exposed to high temperatures and direct sunlight. Figure 16 shows an example of the inaccurate temperature data collected by the HOBO meters. While nighttime, morning and evening temperatures seem reasonable, the spikes that occur around mid-day do not.

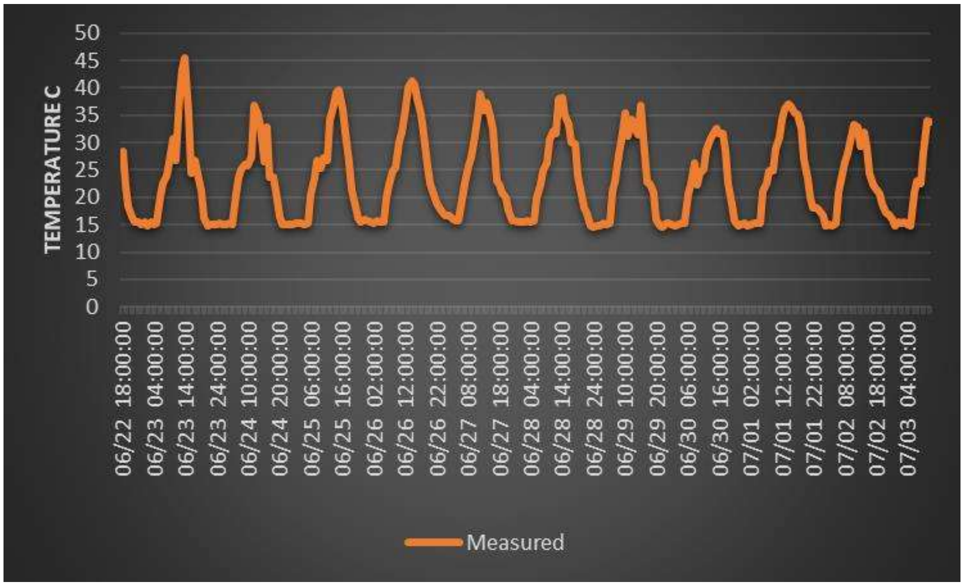


Figure 17: Temperature in Zone 2 measured using a HOBO meter

Temperature measurements were collected with all five HOBO meters and a high accuracy temperature sensor located within a one foot radius. These were placed on the dashboard of car with the doors and windows open. The dashboard method was utilized rather than the actual greenhouse because temperatures on the day of calibration were expected to be much cooler than the hottest days during the monitoring period. It was crucial that the sensors be exposed to both high temperatures and sunlight. Additionally, the dashboard was effective because the glass filtered some light, mimicking the greenhouse cladding. During the calibration period, sensors collected data every five minutes for seven hours from 12:00PM to 7:00PM.

It was found that the simple HOBO meters (the ones that do not collect relative humidity data) experienced a large amount of error at temperatures above 24 degrees Celsius. Figure 17 shows data from each meter and average light measurements over the 7 hour period. Several things are evident. The most obvious is the large discrepancy between the high accuracy meter and the simple HOBO meters (labeled: Zone 1-5). The relative humidity HOBOs (labeled: Zone 1,5 RH) did not perform as poorly. The second is that the high accuracy sensor adjusts much more quickly to changing temperatures and thus has more angular and variable temperature line. The Hobo meters adjust more slowly. Because of this, the largest differences between high accuracy and HOBO measurements occur when light levels drop or increase and temperature changes rapidly. Finally, as light levels and temperature drop, the difference between HOBO meters and high accuracy measurements decreases to zero.

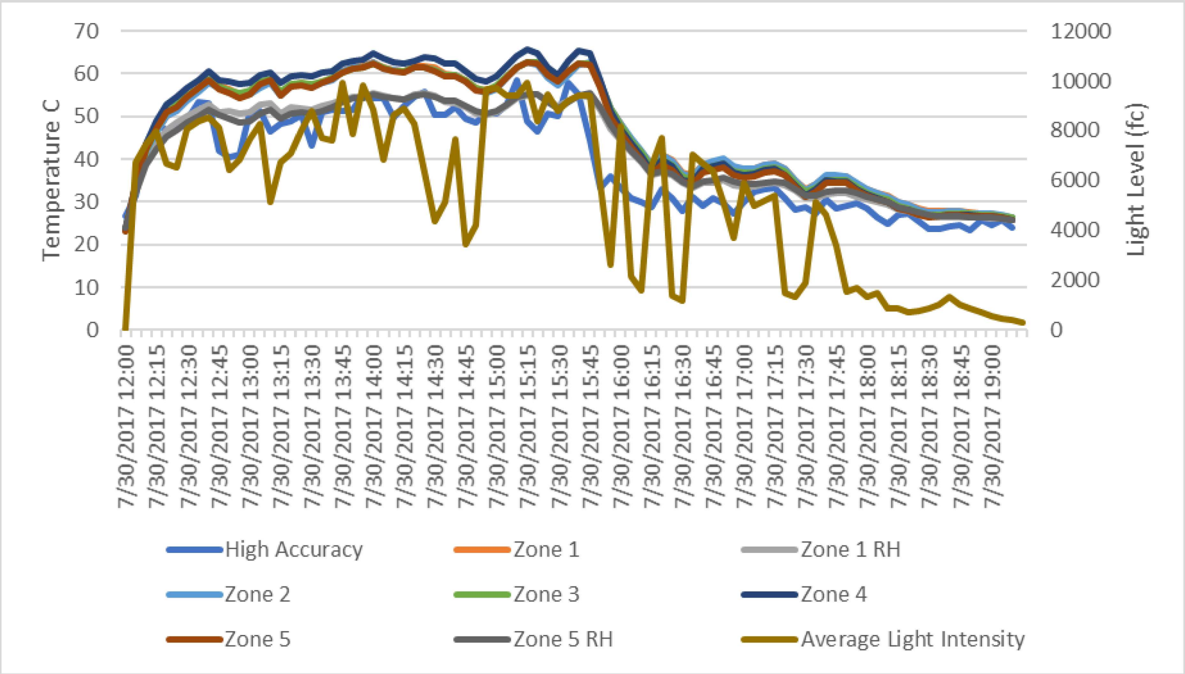


Figure 18: Results of calibration measurements

These observations were used to remove several outliers. Once outliers were removed, a trend for each sensor and its associated temperature and light readings was created. Figure 18 shows the data points that were removed. Six points where removed as the beginning of the monitoring period as sensor adjusted to their environment and eight other points were removed over the course of the remaining 6 hours and 30 minutes.

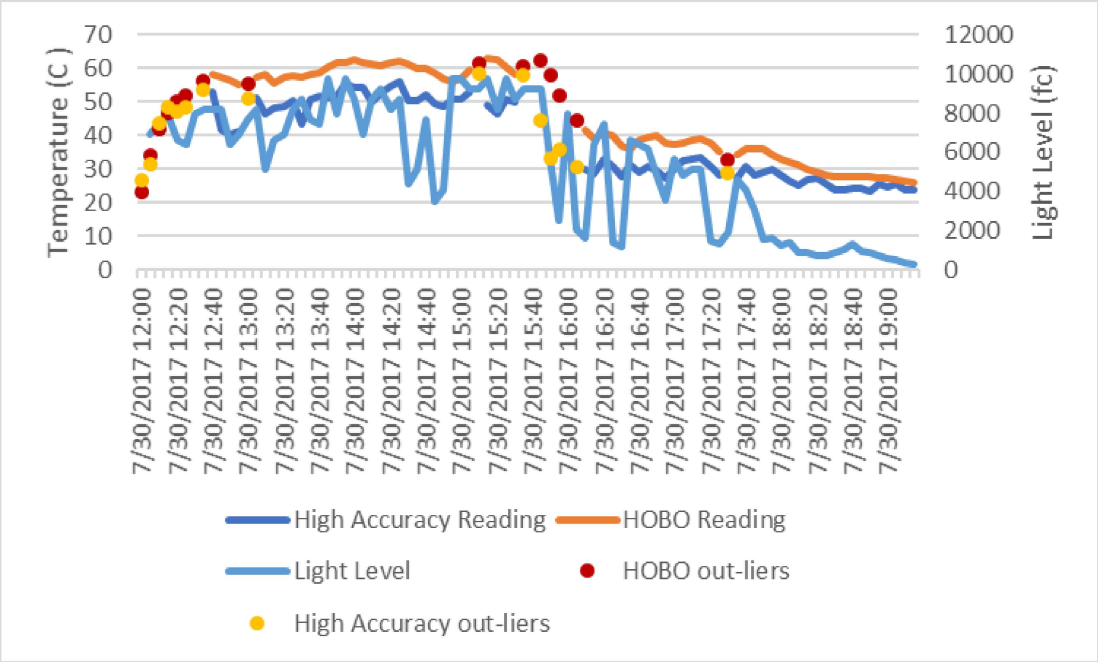


Figure 19: Out-liers removed form data analysis

The rest of the data was graphed in several ways. The strongest correlation was found to be between light intensity and difference between the high accuracy and HOBO meters. One trend was established between the light levels of 0 and 2000 fc and another was established for light levels above 2000. Each sensor was treated independently, and the calibration equations for that sensor was applied to data over the experimental monitoring period (June 22 to July 3). The process for zone 3 is shown here as an example that was followed for each meter. Figure 19 shows a scatter plot of the temperate difference between the HOBO and high accuracy sensor as a function of light intensity. The change that occurs around 2000 fc can be clearly seen.

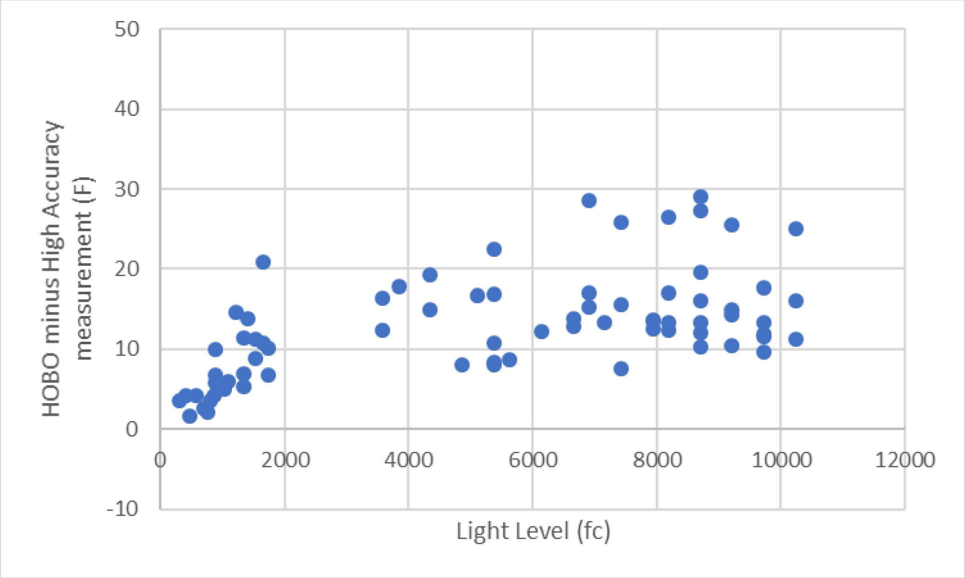


Figure 20: Zone 3 calibration data collected from 12:00 PM to 7:00 PM

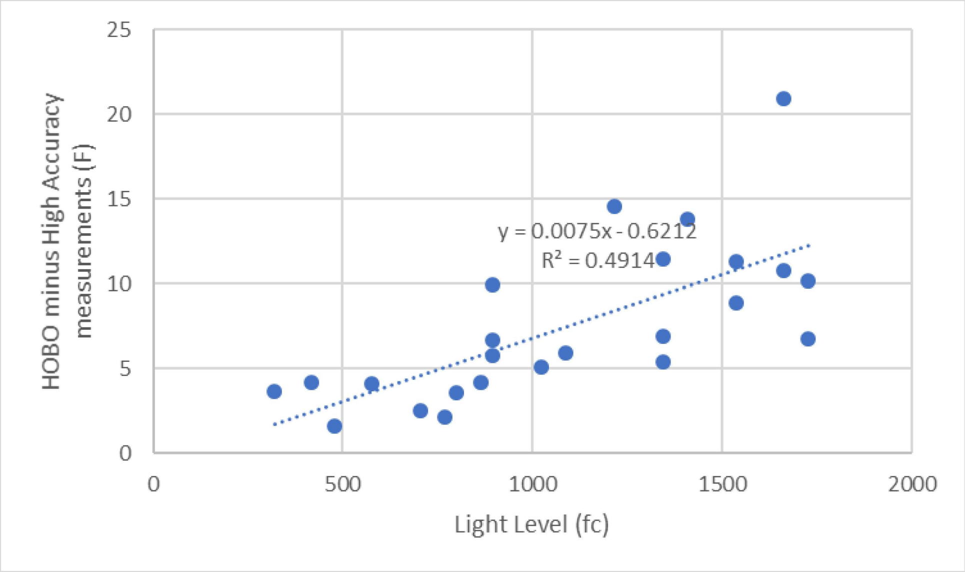


Figure 21: Zone 3 Calibration data graphed as function of light intensity < 2000 fc

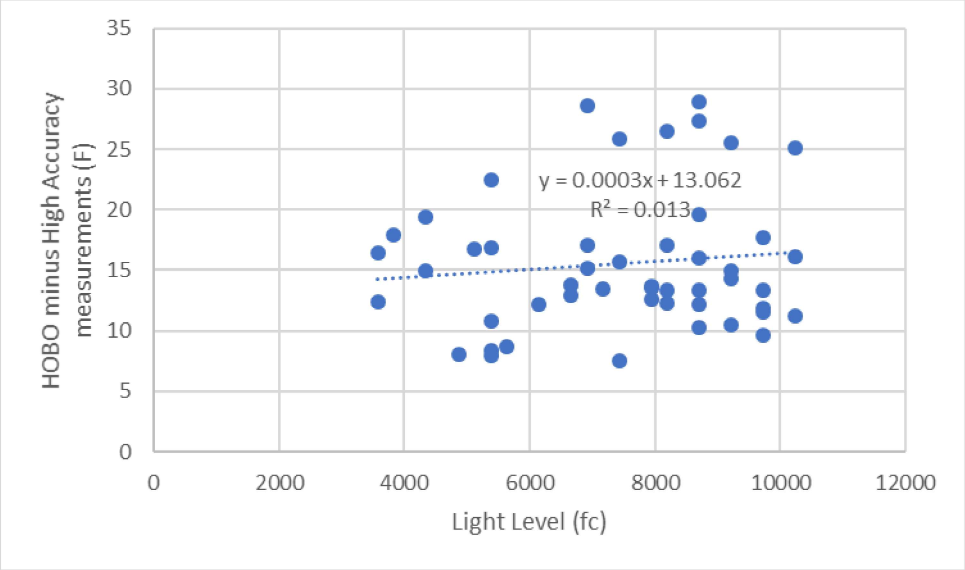


Figure 22: Zone 3 Calibration data graphed as function of light intensity > 2000 fc

Figure 20 and 21 show the piece-wise trend that was established. This was applied first to the calibration data to confirm that the correction was effective and then to the ten-day experimental data. Figure 22 shows the correction applied to the calibration data with original data for a comparison. As you can see from figures 20 and 21, the data was scattered and the R^2 values were large. While this allowed for the data to be analyzed, it represents a very significant degree of uncertainty in the results.

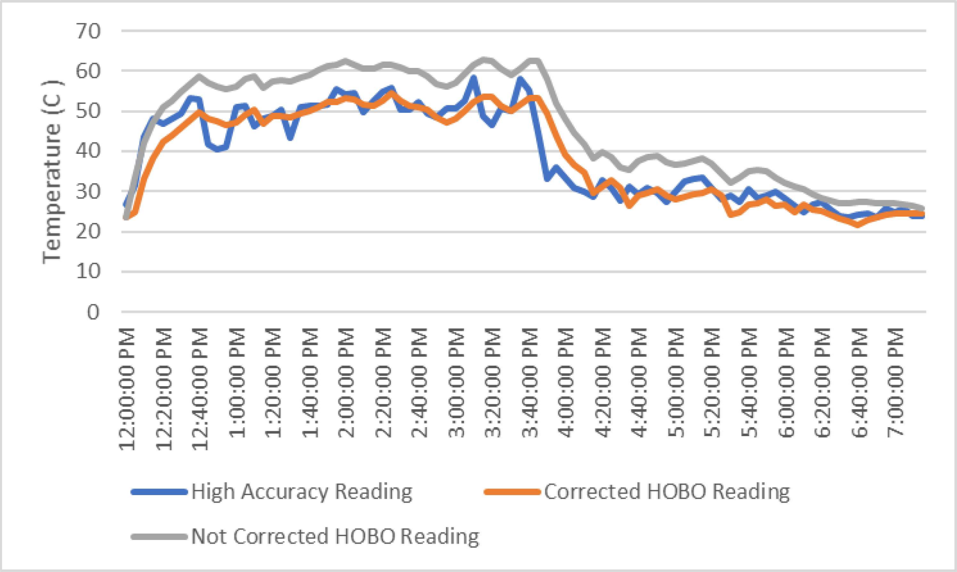


Figure 23: Data collected by the zone 3 HOBO meter before and after calibration compared to the high accuracy sensor data

Similar results were achieved by applying the individual correction formulas for each meter to the calibration data. Table 10 shows the unique equation for each meter. Note that equations and temperature corrections are in degrees Fahrenheit and were converted after application for the sake of consistency throughout the report.

Table 8: Calibration equation for each meter

	Resulting IF / THEN equation
Meter	> 2000 fc < 2000 fc
Zone 1	IF(LL>2000,HT-(0.0002*LL+14.4),HT-(0.0092*LL-.62))
Zone 2	IF(LL>2000,HT-(0.0001*LL+16.4),HT-(0.0078*LL))
Zone 3	IF(LL>2000,HT-(0.0003*LL+13.6),HT-(0.0075*LL))
Zone 4	IF(LL>2000,HT-(0.0009*LL+12.0),HT-(0.0094*LL-1.8))
Zone 5	IF(LL>2000,HT-(0.0005*LL+11.2),HT-(0.0065*LL-0.6))
*LL = Light Level, HT = HOBO Temperature	

The five figures below show the experimental data after calibration (Actual Temp) compared to the EnergyPlus results (Predicted Temp). Measured and predicted results follow similar trends although some differences do occur. In some instances, the difference between predicted and measured temperatures are larger than 10 degrees C. One obvious pattern is that the predicted temperature decreases more slowly during the night and in some cases, increases very slightly before dropping to the set-point of 15 degrees Celsius. This occurs consistently in every zone.

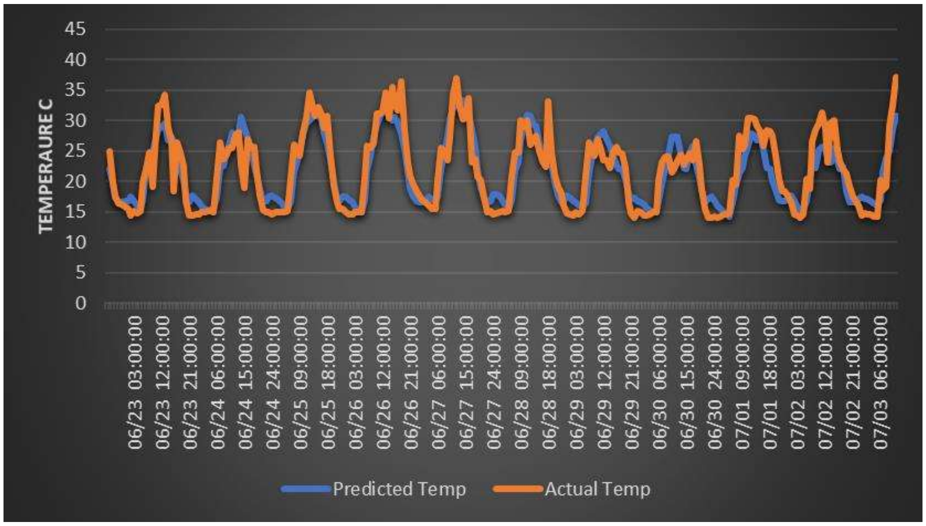


Figure 24: Zone 1 actual and predicted temperature comparison

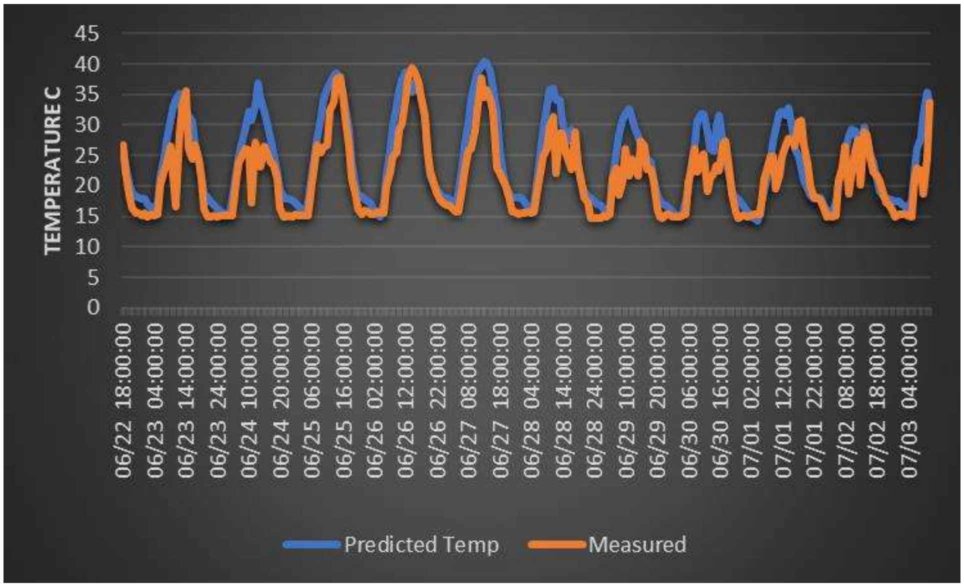


Figure 25: Zone 2 actual and predicted temperature comparison

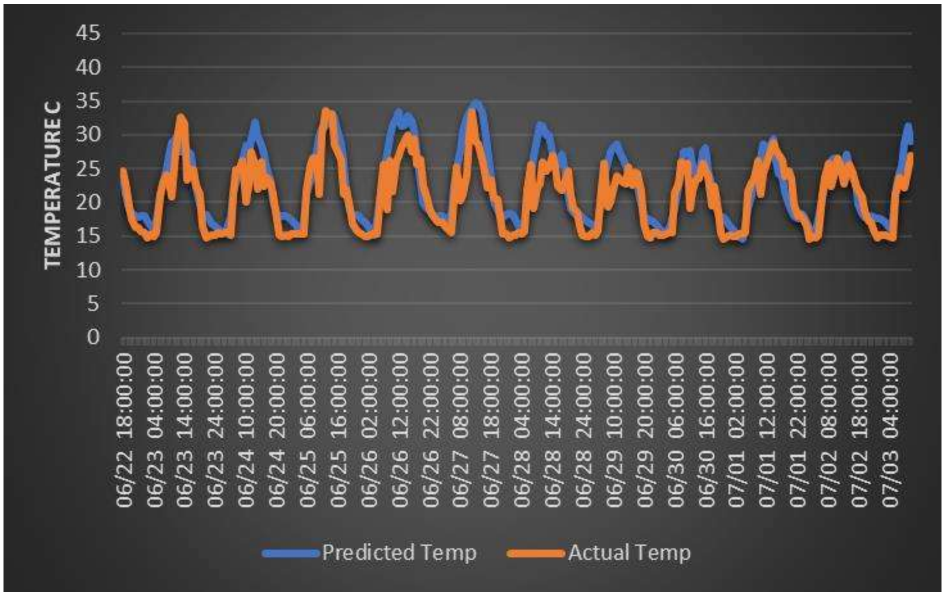


Figure 26: Zone 3 actual and predicted temperature comparison

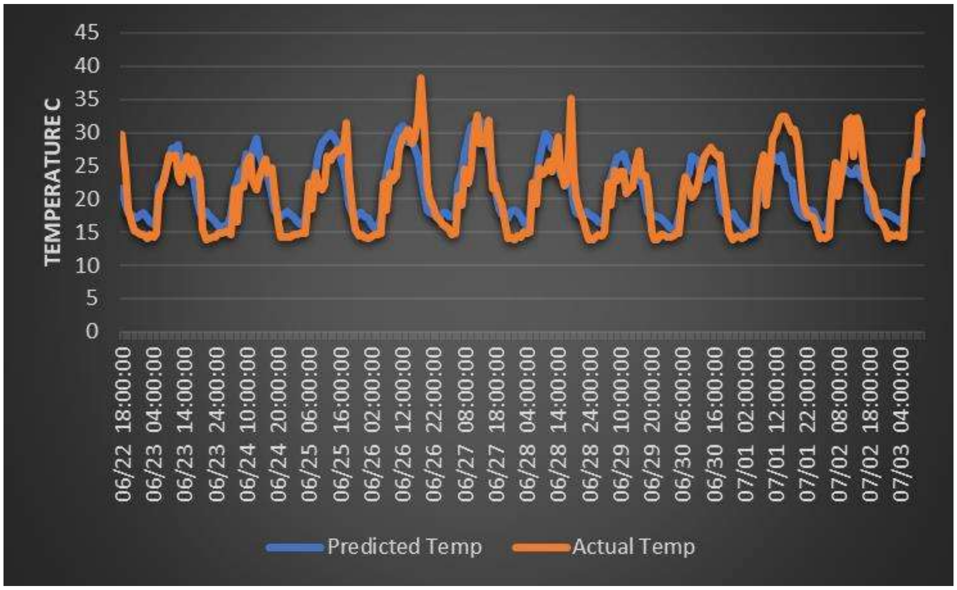


Figure 27: Zone 4 actual and predicted temperature comparison

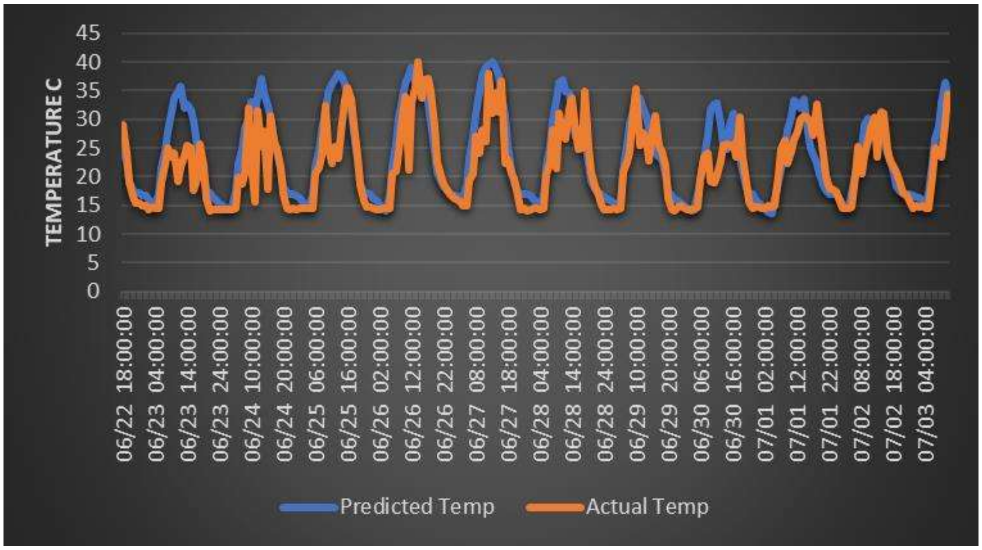


Figure 28: Zone 5 actual and predicted temperature comparison

3.3.2 Relative Humidity

Two sensors collected relative humidity data over the measurement period. Figures 28 show the comparison of relative humidity prediction using EnergyPlus to actual relative humidity collected from zone 1 of the greenhouse. Figure 29 shows a similar graph for zone 5. Results from both the simulation and the measurements show that relative humidity spikes in the middle of the night and falls as low as 10 percent during the middle of the day, but the actual relative humidity reaches much higher levels than the predicted RH.

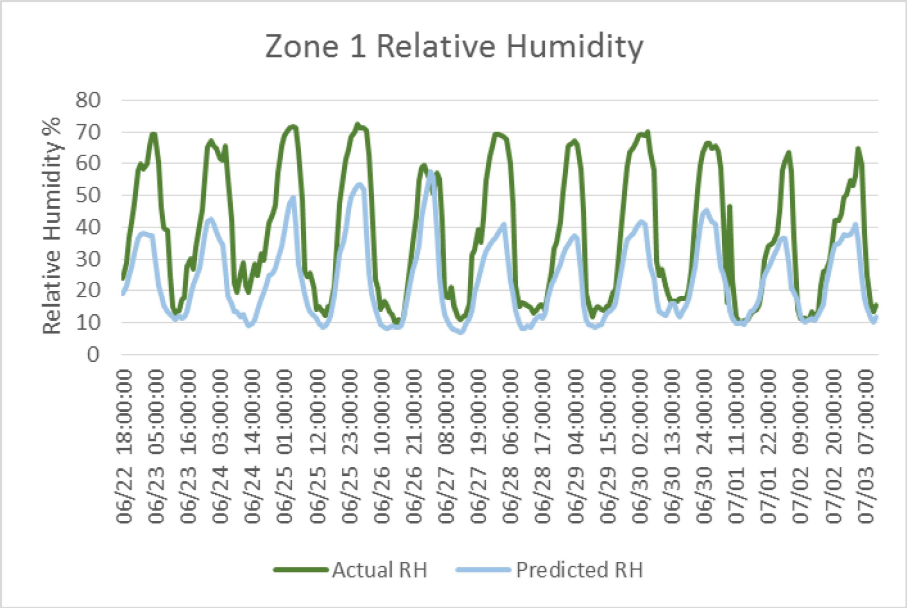


Figure 29: Zone 1 actual and predicted relative humidity comparison

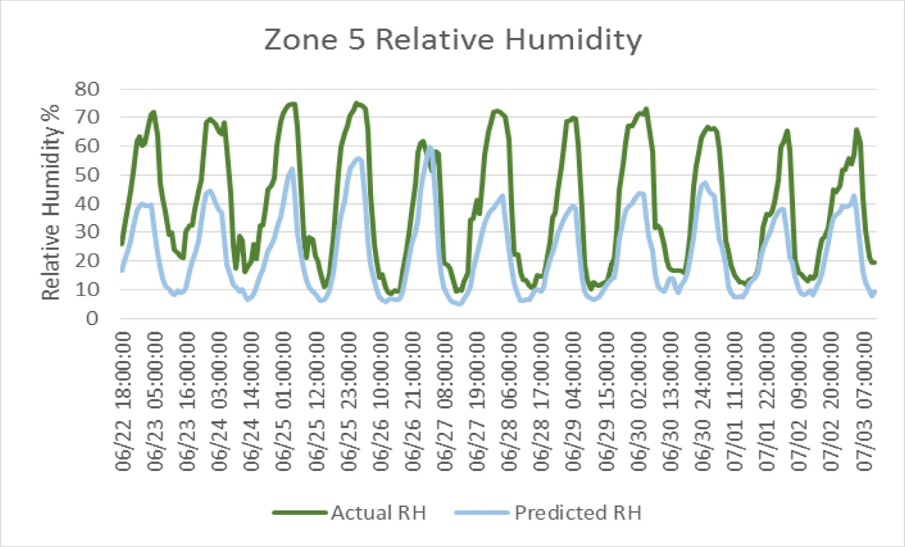


Figure 31: Zone 5 comparison of actual and predicted relative humidity

3.3.3 Energy

Energy results from the EnergyPlus model are within 5% of those estimated from the Greenhouse data. Energy estimations for the University of Wyoming greenhouse was calculated using the MetaSystem data. Since all equipment influencing the greenhouse environment is controlled by on/ off commands, the MetaSystem data for each component was simply the date and time of each command. This data was separated into hourly intervals with status indicated by 0 (on) or 1 (off). This allowed the status of the equipment to be plotted against other data that occurred in the experiment. Finally, specifications for each component were obtained and energy consumption of each component was multiplied by its hourly status. Hourly component energy consumptions were combined for a total greenhouse energy consumption.

Figure 30 shows when mechanical systems are running compared the energy totals from EnergyPlus. Although the EnergyPlus simulation did not exactly replicated the action of the mechanical systems, it shows many critical similarities such as dips when mechanical systems switched off.

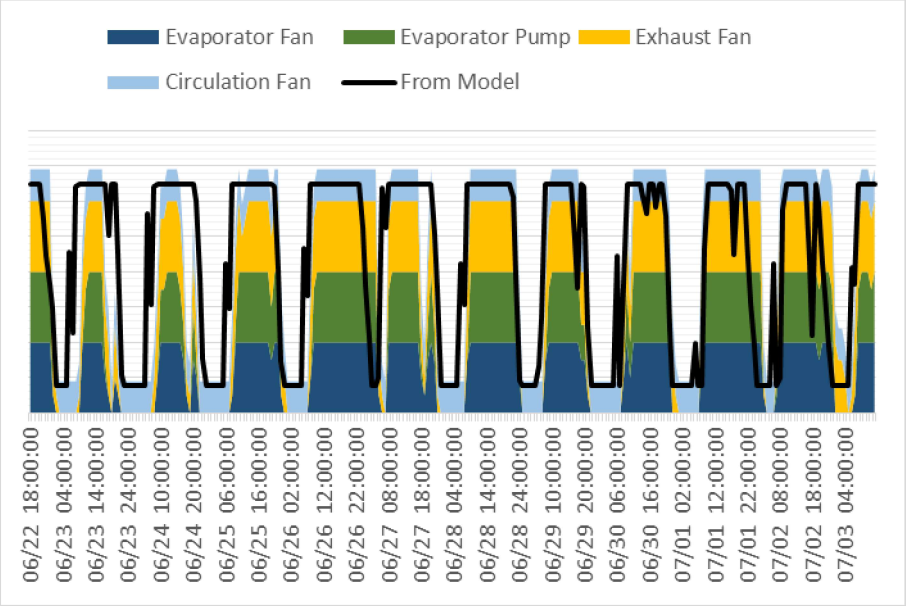


Figure 33: Measured operation of mechanical systems and energy intensity output calculated from EnergyPlus model

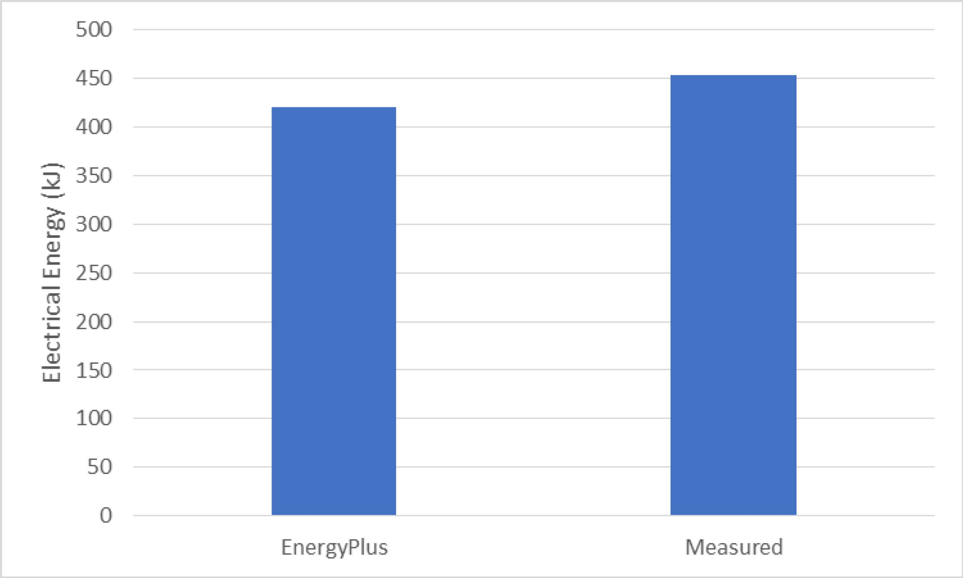


Figure 34: Predicted and actual energy consumption over the simulation period June 22 to July 3, 2017

Total electrical energy consumption was represented to within 5% by EnergyPlus, as shown in Figure 31. Although the EnergyPlus model calculated a slightly lower energy consumption this was coupled with more consistent climate control.

3.4 Discussion

This study found that EnergyPlus was able to predict temperature trends within the greenhouse. However, relative humidity was not accurately represented by EnergyPlus. Plant transpiration, exposed soil and open water containers contribute to high humidity levels in greenhouses. This model was not able to capture this phenomenon. Despite the attempt to incorporate some of the EnergyPlus features intended to represent water within a space, predicted relative humidity was consistently lower then actually relative humidity levels. During the night hours, the difference between predicted and measured grew as large as 30 percent. This difference demonstrates that the EnergyPlus strategies used in this study do not effectively capture some aspects of the greenhouse environment. Not only does relative humidity play a large role in plant health and growth, it also has a large effect on latent heating a cooling loads. It is likely that this contributes to the difference found when comparing measured and predicted temperatures.

There are also many limitations to this study. The experiment took place over a short measurement and simulation period which only represented summer performance of the greenhouse. This is a major limitation because winter performance was not considered. Ideally, the greenhouse would be monitored and the simulation would be run over the course of an entire year to determine how well the simulation was correlated to the greenhouse under all conditions. An infiltration of 7 ACH50 was assumed without conducting a blower door. In an old and poorly regulated structure such as the University of Wyoming greenhouse, it is possible that infiltration could be twice the assumed value. Although this study found that infiltration did not have a large effect on the results, the infiltration would be a much more important factor when the outdoor air is very cold. At the time of monitoring, the temperature difference between the outdoor and interior air was less than twenty degrees. During the winter the temperature in Laramie WY can drop as low as -30 Celsius with a significant wind chill factor. Infiltration of air 40 degrees colder would have a very different effect. A blower door test is highly suggested for future research.

Additionally, many assumptions were made concerning performance of materials, construction and mechanical equipment. One of the largest factors contributing to the cooling load in the space was the transmittance and reflective properties of the glazing material. Assuming that the old, dirty siding acts like a new material is not likely accurate. Similarly, the mechanical equipment was based off of the original specifications and does not take into account inefficiencies due to ware. To draw final conclusions, further experimentation is needed. It is possible that a newly constructed, high tech greenhouse would be more accurately represented by EnergyPlus. The University of Wyoming greenhouse has a gravel floor, old siding, and many other factors that contribute to its unpredictability. It would be very beneficial to test EnergyPlus on a high-tech facility that is constructed more closely to the standards of a traditional building.

Another potential inaccuracy is the comparison of mechanical system energy consumption using only hours of operation and technical specifications. It is very likely that after many years of use the equipment is much less efficient. Because the University of Wyoming does not have power metering on its individual space let alone individual equipment, determining the true energy use of the greenhouse was not possible.

Finally, a major limitation was the inaccuracy of the HOBO meters. Although the HOBO sensors which measured relative humidity seemed to performed to an acceptable degree, their accuracy should be verified again before future use. The simple HOBO meters are not recommended for use at temperatures above 26 degrees Celsius and in direct light.

In conclusion, much more research needs to be conducted before approving or disapproving EnergyPlus as a platform for greenhouse research. Although this experiment found that EnergyPlus can simulate temperature and energy consumption, there are many other parameters that determine the functionality of greenhouses.

Chapter 4 Energy Savings Analysis: a Greenhouse Heated by Waste Heat

Due to inherent inefficiency, industrial processes lose a large percent of their productivity to waste heat. Waste heat is "heat that is either lost through the flue stack of an industrial operation, or which is rejected from a power generation station to improve the thermodynamic efficiency of the cycle" [2]. Although it is not technically and economically feasible to recover all waste heat, a gross estimate is that waste-heat recovery could replace 9% of total energy used by US industry [125]. Instead, waste heat is often discharged into nearby streams, rivers and other heat sinks, creating many ecological issues. Utilization of this heat through greenhouse heating can offset the cost of cooling industrial equipment as well as have a beneficial environmental impact [126].

In this study, EnergyPlus is used to simulate the indoor environmental conditions and predict energy use of a 3-acre greenhouse located in Lovell, Wyoming. Large amount of waste heat is available from a local sugar plant. We first conducted a feasibility study on utilizing waste heat for the greenhouse and then designed mechanical systems for the greenhouse to evaluate the overall system efficiency for the greenhouse.

4.1 Simulation

During the winter beet processing campaign, the sugar plant discharges hot water at an average temperature of 115°F (46°C) and an average flow rate of two million gallons per day. Currently, the water must be cooled to below 80°F (26.7 °C) before it is discharged into the river. The waste heat represents a significant opportunity to save energy and money.

Available heating energy was calculated for the winter months based on monthly flow rates. Temperature difference and specific heat remained the same while mass flow rate varied. Table 9 shows the resulting available heat energy.

Table 9: Monthly Available Heat Energy from Western Sugar

Month	Volumetric Flow Rate [Mgal/day]	Mass Flow Rate [kg/hr]	Resulting Heat Energy [GJ/hr]	Resulting Heat Energy [MBtu/hr]
September	2.95	462,085.5	32.19	30.51
October	3.54	554,502.6	38.62	36.61
November	1.74	272,552.1	18.98	19.99
December	1.32	206,763.7	14.40	13.65
January	1.62	253,755.4	17.68	16.75
February	1.75	274,118.5	19.09	18.10

EnergyPlus was employed for the feasibility study. In an initial parametric study of greenhouse sizes (1, 2, and 3 acres), a greenhouse was used to determine if the available waste heat was sufficient to cover annual heating loads [124]. Springing off of this model, a more complex model was created and mechanical systems simulated in EnergyPlus.

4.2 Geometry

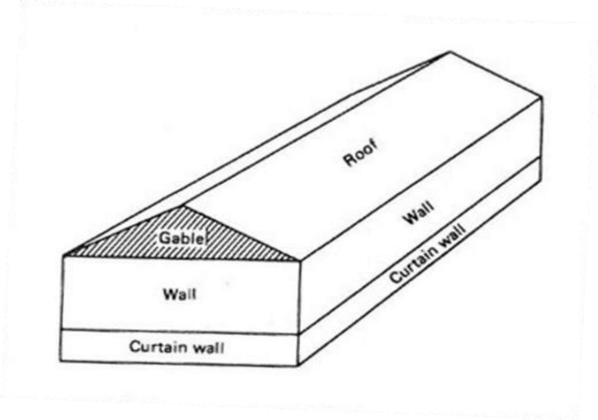


Figure 35: Typical A-frame greenhouse geometry

Modern greenhouses are made of a variety of materials, each with a range of advantages and disadvantages. In addition, there are a variety of forms a greenhouse can take, including an A-frame shape to a Quonset style. In an A-frame greenhouse, there are four components in its construction to consider: the roof, gable, wall, and curtain wall [92]. For the purposes of this engineering study, it was assumed that the greenhouse would be A-frame. It was also assumed that the greenhouse, would have a series of pitches, or gables, forming 15 bays. These gables are located at the top of the 20 foot wall, are 30 feet wide and 10 feet tall. Figure 32 shows the geometry of the A-frame bays.

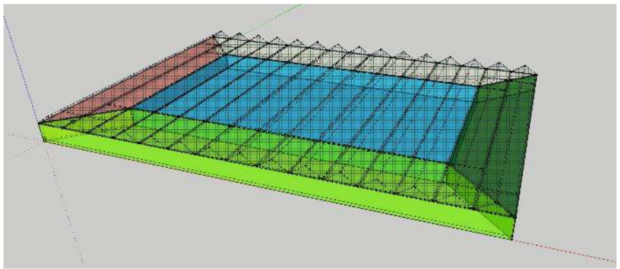


Figure 36: the SketchUp geometry and zone division

The 3-acre, 15 bay greenhouse was modelled in SketchUp using the OpenStudio plug in. The occupied space was divided into five thermal zones; four perimeters and one large central zone. The unconditioned bays were considered a sixth zone. Figure 33 shows how the SketchUp geometry and zone division. In order to simulate realistic air mixing, operable windows were created on all surfaces between zones and an airflow network was created in EnergyPlus.

4.3 Mechanical Systems

An ideal air load model was used to estimate the heating energy consumption and as a consistent starting point for mechanical system implementation. All construction modifications, material updates, and airflow networks, were made prior to mechanical system design. Once the basic model was completed, mechanical systems were added. Two models with variable air volume systems and one model with water to air heat pumps were created. Model 1 had a VAV system with electrical components. This model was used as an example of standard practice with which to compare innovative systems which utilize waste heat. Model 2 had a VAV system with hot water heating coil and reheat coils. This model represented a greenhouse with VAV in which the waste heat water was utilized. The third system, Model 3, was designed with five water to air heat pumps. In Model 2 and 3, the waste heat water was modelled as a gas fired boiler.

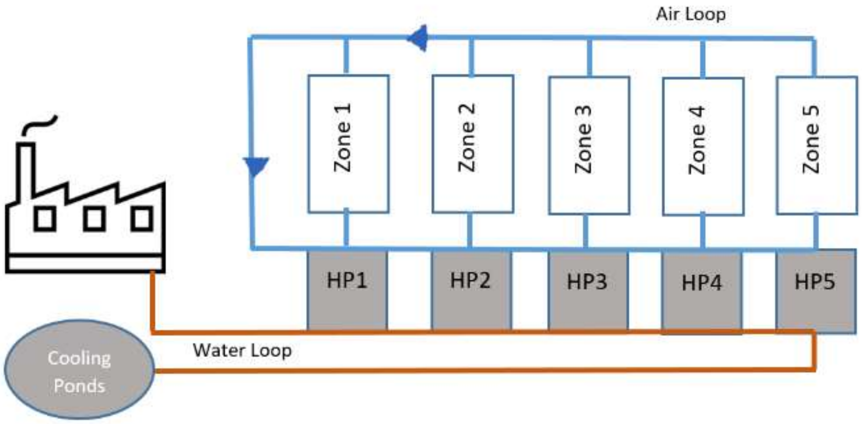


Figure 37: Schematic system diagram for water to air heat pump using waste heat

Water to air heat pumps were selected as the best option for several reasons. Most importantly, the heat pump system can efficiently transfer heat to the air. This is due to the high coefficient of performance. Additionally, the heat pumps offer flexibility and the potential for water stored during the day to be used at night. Even if the temperature of the water drops significantly in storage, the heat pumps can raise the temperature of the air without the use of backup electric coils. This would be practical for actual application. A simplified diagram of the waste heat system is shown in figure 34.

In the simulation, the waste heat source (gas-fired boiler) provided 46°C (114.8°F) water to the VAV and water to air heat pumps in Models 2 and 3 respectively. Nominal heating coefficient of performance (COP) for the water to air heat pump is 4.2. A year-long energy simulation was conducted for Cody, Wyoming with TMY (Typical Meteorological Year) weather data. Temperature set point were 70.0°F (21.1°C) at night and 80.0°F (26.7°C) during the day.

4.4 Results

Simulation results support initial calculations suggesting that available waste heat will provide a large percent of the required heating. Furthermore, results indicate that heating energy consumption in the 3-acre greenhouse could be reduced by 67% through the utilization of waste heat and water to air heat pumps.

The demand for waste heat varies throughout a typical day based on the outdoor temperature and temperature set points for the greenhouse space. Figure 4 shows the heating demand for the greenhouse space in comparison with available waste heat from industry for a typical winter day. In this graph the heating demand represents joules of heat energy transferred from the waste heat water to the space. The hourly heating demand is well below the available waste heat at any point during the day.

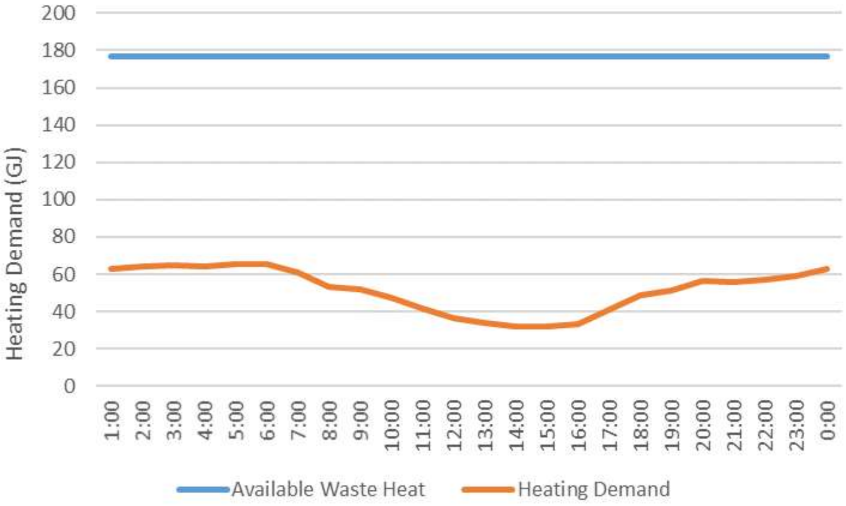


Figure 38: Comparison of hourly heating demand and available waste heat in a typical winter day (Jan. 3rd.)

A comparison of the total annual energy consumption of the three systems shows a large energy improvement of both waste heat systems over the electric VAV system. Figure 35 shows the annual heating electrical consumption for the three models. Additionally, the heat pumps system was found to be more efficient then the VAV system with waste heat source. This was because the VAV system required the fans and pumps to work much harder. The heat pump system used approximately 1200 GJ of electricity per year for fans and pumps while the VAV system used over 8000 GJ. Including all electric components such as compressors, reheat coils, fans and pumps, electricity consumption was 13780 GJ for the electric VAV system, 9057 GJ for the VAV system with waste heat utilization and 5983 GJ for the heat pump, waste heat system.

4.4.1 Comparison of Electric VAV and Heat Pump Systems

A 67% reduction in electrical consumption from the electric VAV system (System 1) to the WAHP system coupled with waste heat source (System 3) was calculated by comparing the total electrical energy required to maintain the heating set points for both systems over the course of a year. This comparison could be made because all components of both systems were specified as electrical. The total electrical energy for the water to air heat pump system includes power for pumps, fans and supplementary electric heating coils. The quantity of energy provided by the waste heat (gas fired boiler) is not included in the total energy consumption calculation because it is considered free heat. Figure 36 shows the yearly electrical heating energy consumption of the electric variable air volume system and the water to air heat pump system. It is clear from figure 37 that there is a significant reduction in both electrical heating energy and energy consumption variability with the heat pump system.

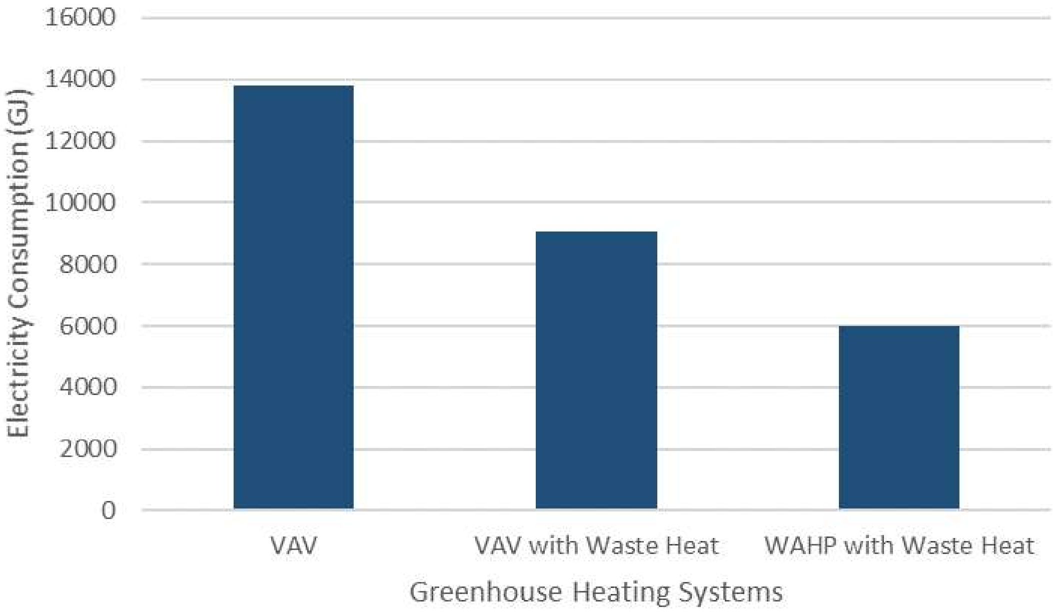


Figure 39: Annual Electricity used for Heating

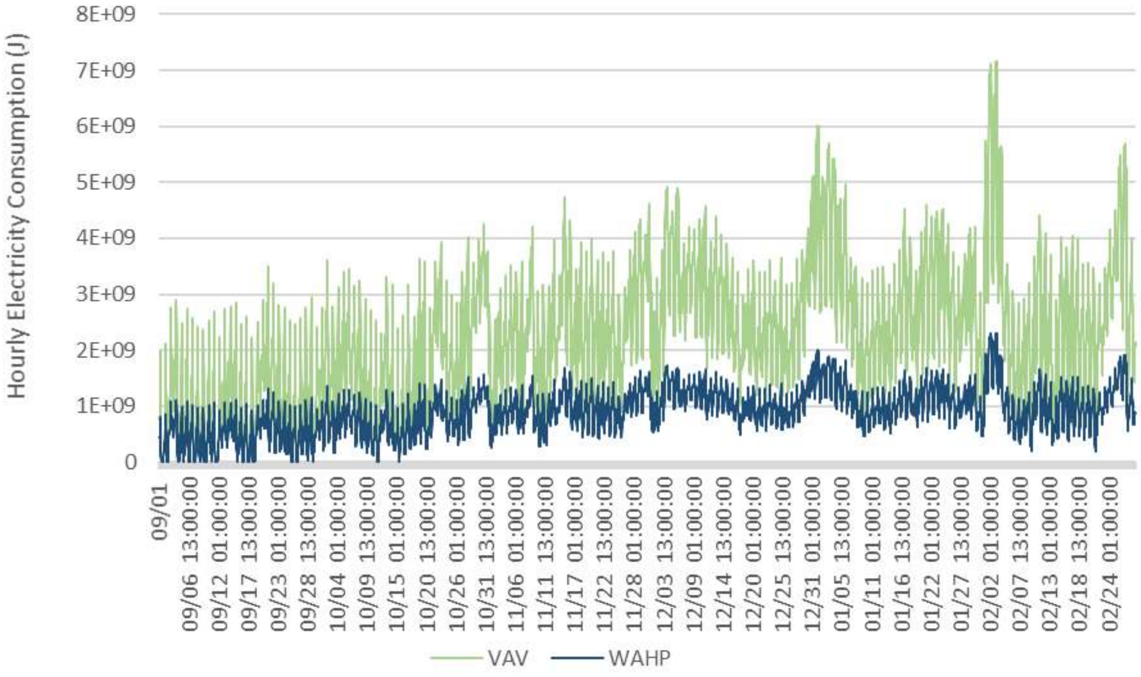


Figure 40: Comparison of Hourly Electric Consumption for electric VAV system and Water to Air Heat Pump system for Winter Months.

Annually, the electric VAV system consumes 13,780.02 GJ of heating energy while the WAHP system only consumes 5982.99 GJ. Figure38 shows the hourly electrical consumption of the WAHP system vs. the electrical VAV system over the course of a typical winter day.

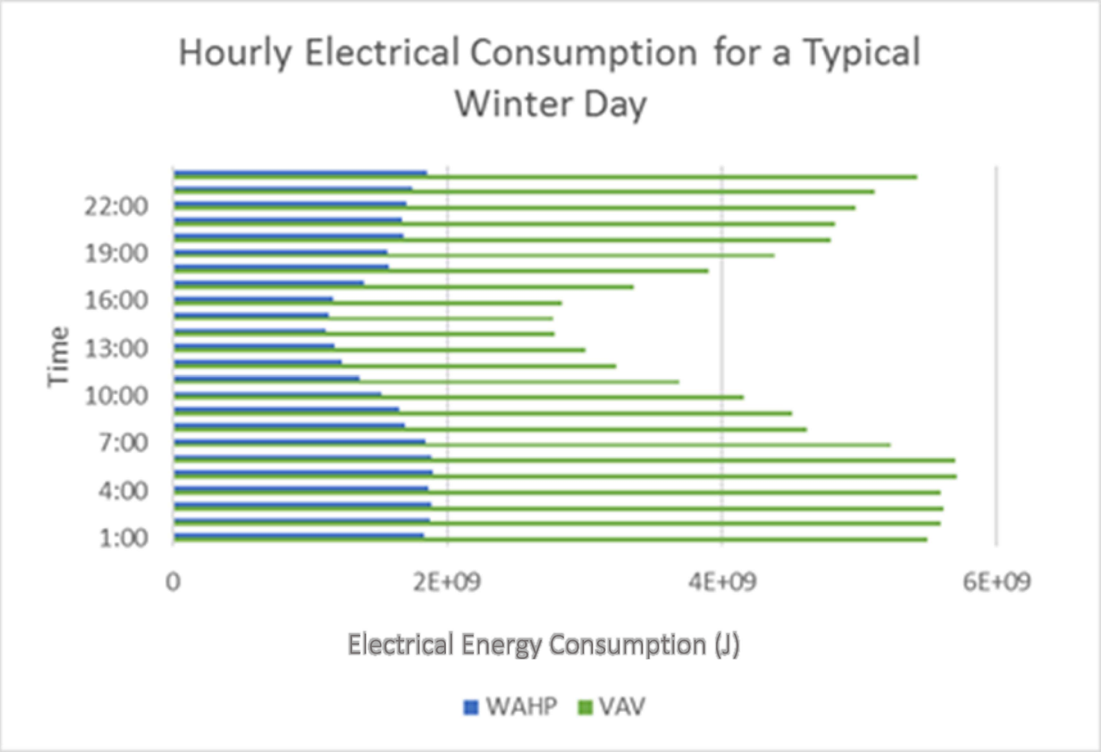


Figure 41: WAHP vs. VAV Hourly Electrical Consumption for Jan. 3rd

A closer look at the simulation results show that the heat pump model is able to maintain temperature set points. Figure 39 shows the outdoor temperature as compared to the interior zone temperature as regulated by the VAV and WAHP waste heat system. The line representing VAV zone temperature overlaps with the line for WAHP zone air temperature.

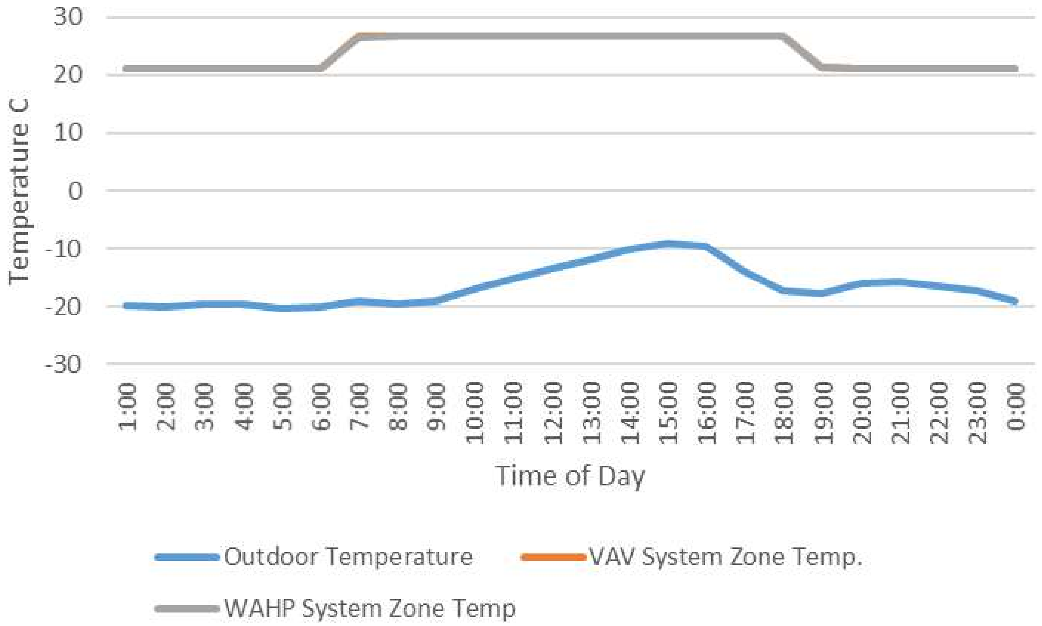


Figure 42: Outdoor Vs. Controlled Indoor Air Temperature for VAV and WAHP Systems on a typical winter day

Based on these results, the waste heat source provides more than enough heat to maintain the greenhouse temperature, but there are still challenges associated with transfer of the heat from the water to the interior space. This model utilized a water to air heat pump with a COP of 4.2 and was able to achieve an electricity reduction of 67% over a VAV system with electrical heating components.

4.5 Discussion

The results show a significant potential for greenhouses to save energy through waste heat utilization. The 67 % reduction in annual heating energy, as show in figure 40, could make greenhouse feasible in many more locations and cold climate urban areas.

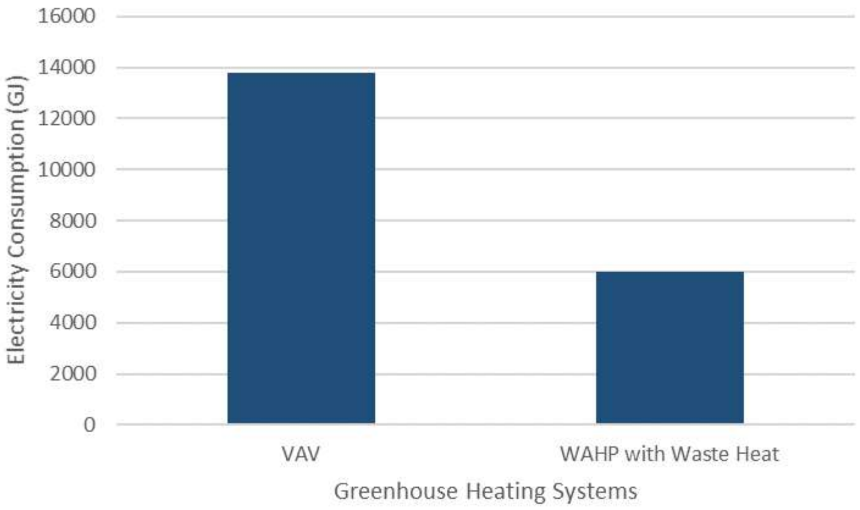


Figure 43: Annual Electricity Consumption for heating of electric VAV vs. WAHP, Waste Heat System

Advances like waste heat utilization in greenhouse technology are crucial for several reasons. As our environment continues to change, food security in urban and rural areas particularly in cold or harsh climates becomes a growing concern. The demand for food is expected to double in the next fifty years. As this demand grows the amount of land available for agriculture decreases. Greenhouses offer greater yield per area, decreased water consumption and protection from pests and disease. However, greenhouses are only feasible if we can decrease the amount of energy necessary for operation. Waste heat is one possible solution. This feasibility study demonstrates the great potential of this technology and opens the door for a more main stream form of greenhouse energy modelling.

There are several limitations to this study what will be the focus of future simulations. First the interaction between crops and greenhouse controlled environment were not an integral part of this study. Furthermore, control operation for the mechanical systems of the greenhouse should be optimized and other types of mechanical systems should be considered in future study. Most importantly, further validation is needed to confirm the results of simulations. If this project is complete, the results from the simulation can be compared and the accuracy determined.

Chapter 5 Summary of Research and Conclusions

Controlled environment agriculture is a promising field in terms of both worldwide energy use reduction and food security. However, there are many hurdles that must be overcome if CEA is to be more sustainable then open field agriculture. A comparison of these two systems through life cycle analysis and input-output analysis suggests that the incorporation of renewable resources can help to offset the increased energy consumption of greenhouses and make them feasible. Ideally, the technology of the greenhouse can improve the yield and increase profit more than the upfront and operational cost. This is, however, a delicate balance.

As technology evolves and more options are available, the benefits of technological upgrades can only be weighed against the costs if designers can predict how a structure will perform and effect the plants before it is built. This is a crucial step along the road to sustainable agriculture and is currently understudied and difficult. Modeling of the greenhouse environment is one way to approach prediction but, literature review suggests that there are several things that significantly limit the exchange of information using greenhouse modeling. The first is the lack of consistency in the type of model used. Each model returns different, parameters, units, time steps and levels of accuracy. Similar the models vary in reliability. While some use complex geometry or advanced computational fluid dynamics, other are as simple as a series of heat transfer equations. Additionally, each study makes different assumptions and realize on a variety of human inputs that are not often consistent. Finally, many of the most commonly used modeling tools are not adapted to take into consideration the unique parameters of greenhouses. For example, effects of high levels of moisture and air velocity on plants are difficult to predict.

Advanced energy modeling is a very complex field that requires a good deal of specialized knowledge and practice. The cultural requirements of specific plants and an understanding of the growing environment, is an equally specialized branch of science. Thus, accurately predicting the greenhouse environment is a multi-disciplinary challenge that requires communication between both parties. The path along which building science, modeling, and biology meet is rarely walked outside the field of controlled environment agriculture and leads to a desert where building information modeling is rarely applied. As such, greenhouse modeling is limited to a handful of academic studies and isolated tools created by industry.

In this study, an energy plus model was created and compared with an existing greenhouse to validate that the model results were an accurate representation of a greenhouse environment. Results showed that there was a good agreement between the EnergyPlus model and the university of Wyoming greenhouse for both indoor temperature and energy use. However more research needs to be conducted when calibrating relative humidity and carbon dioxide results. Additionally, EnergyPlus was used to determine the energy savings that could be achieved by using waste heat from industrial processes to heat a greenhouse. A three acres greenhouse in Lovell Wyoming was modeled with mechanical systems designed to harvest heat from Western sugar, an on-site sugar processing plant. It was determined that over 60 percent of electrical energy for heating could be could be reduced through the utilization of waste heat.

It can be concluded that to accurately represent the greenhouse environment using EnergyPlus, advanced modeling techniques and many cases of validation will be necessary. However, based on this research it is likely that a set of general techniques could be established and used as instruction for future models. This would be greatly beneficial to the field of controlled environment agriculture because it would help to establish a widely accessible and commonly used platform on which to conduct research.

It is recommended that future research make significant efforts to contact architects, engineers and commercial entities to understand other modeling techniques applied to the field of controlled environment agriculture. Although the industry leader contacted during this research were unwilling or did not have sufficient time to contribute information, it expected that a wealth of knowledge exists within these sources. If knowledge that has been gained over years of experience could be collected, bought together and made public through academia, it would encourage future research and advance the field.

Open field agriculture is one of the most environmentally devastating sectors of society. Between, direct energy use for planting, harvesting and transportation, fertilization and pesticide leaching, water consumption, genetic modified species, and the vast areas of land that have been deforested or converted from their original ecosystems into farm lands, the effects are immense. Today the availability of arable land is decreasing due to over farming while the demand for food is rapidly increasing. This imbalance indicates the need for a dramatic change in agricultural systems worldwide. Greenhouse food production has the potential to lesson or eliminate many of these devastating effects by reducing water consumption and the need for pesticides and fertilizers. Most importantly, the yield per square area of greenhouse can be many times that of open field agriculture. This could cut the area needed to produce the same amount of food to a fraction of what it is now and make it feasible to support a larger population.

References

[1] Davis, N., 1985, “Controlled-Environment Agriculture-Past, Present and Future,” Food Technol. USA.

[2] Andrews, R., and Pearce, J. M., 2011, “Environmental and Economic Assessment of a Greenhouse Waste Heat Exchange,” J. Clean. Prod., **19**(13), pp. 1446–1454.

[3] Vadiee, A., Yaghoubi, M., Sardella, M., and Farjam, P., 2015, “Energy Analysis of Fuel Cell System for Commercial Greenhouse Application – A Feasibility Study,” Energy Convers. Manag., **89**, pp. 925–932.

[4] 2017, “Food Security | Food and Nutrition Technical Assistance III Project (FANTA)” [Online]. Available: https://www.fantaproject.org/focus-areas/food-security. [Accessed: 14-Jun-2017].

[5] Lal, R., 2013, “Food Security in a Changing Climate,” Ecohydrol. Hydrobiol., **13**(1), pp. 8–21.

[6] Gerbens-Leenes, P. W., and Nonhebel, S., 2002, “Consumption Patterns and Their Effects on Land Required for Food,” Ecol. Econ., **42**(1), pp. 185–199.

[7] 2006, *World Agriculture: Towards 2030/2050*, Food and Agriculture Organization of the UN, Rome.

[8] Trenberth, K. E., 2011, “Changes in Precipitation with Climate Change,” Clim. Res., **47**(1/2), pp. 123–138.

[9] Gruber, J., “6 Key Investment Themes For The Next Decade,” Forbes [Online]. Available: https://www.forbes.com/sites/jamesgruber/2013/10/06/6-key-investment-themes/. [Accessed: 15-Sep-2017].

[10] Adams, R. M., Rosenzweig, C., Peart, R., Ritchie, J. T., McCarl, B. A., and al, et, 1990, “Global Climate Change and US Agriculture,” Nat. Lond., **345**(6272), p. 219.

[11] Decker, W. L., Jones, V. K., and Achutuni, R., 1986, “The Impact of Climate Change from Increased Atmospheric Carbon Dioxide on American Agriculture.”

[12] Rosenzweig, C., 1990, “Crop Response to Climate Change in the Southern Great Plains: A Simulation Study*,” Prof. Geogr., **42**(1), pp. 20–37.

[13] Kaiser, H. M., Riha, S. J., Wilks, D. S., Rossiter, D. G., and Sampath, R., 1993, “A Farm-Level Analysis of Economic and Agronomic Impacts of Gradual Climate Warming,” Am. J. Agric. Econ., **75**(2), pp. 387–398.

[14] Reilly, J. M., Hohmann, N., and Kane, S., 1993, *Climate Change and Agriculture : Global and Regional Effects Using an Economic Model of International Trade*, MIT Center for Energy and Environmental Policy Research.

[15] Mendelsohn, R., Nordhaus, W. D., and Shaw, D., 1994, “The Impact of Global Warming on Agriculture: A Ricardian Analysis,” Am. Econ. Rev., **84**(4), pp. 753–771.

[16] Adams, R. M., Fleming, R. A., Chang, C.-C., McCarl, B. A., and Rosenzweig, C., 1995, “A Reassessment of the Economic Effects of Global Climate Change on U.S. Agriculture,” Clim. Change, **30**(2), pp. 147–167.

[17] Reilly, J., Tubiello, F., McCarl, B., Abler, D., Darwin, R., Fuglie, K., Hollinger, S., Izaurralde, C., Jagtap, S., Jones, J., Mearns, L., Ojima, D., Paul, E., Paustian, K., Riha, S., Rosenberg, N., and Rosenzweig, C., 2003, “U.S. Agriculture and Climate Change: New Results,” Clim. Change, **57**(1–2), pp. 43–67.

[18] Tubiello, F. N., Rosenzweig, C., Goldberg, R. A., Jagtap, S., and Jones, J. W., 2002, “Effects of Climate Change on US Crop Production: Simulation Results Using Two Different GCM Scenarios. Part I: Wheat, Potato, Maize, and Citrus,” Clim. Res., **20**(3), pp. 259–270.

[19] Ewert, F., Rounsevell, M. D. A., Reginster, I., Metzger, M. J., and Leemans, R., 2005, “Future Scenarios of European Agricultural Land Use,” Agric. Ecosyst. Environ., **107**(2), pp. 101–116.

[20] Falloon, P., and Betts, R., 2010, “Climate Impacts on European Agriculture and Water Management in the Context of Adaptation and mitigation—The Importance of an Integrated Approach,” Sci. Total Environ., **408**(23), pp. 5667–5687.

[21] Maracchi, G., Sirotenko, O., and Bindi, M., 2005, “Impacts of Present and Future Climate Variability on Agriculture and Forestry in the Temperate Regions: Europe,” *Increasing Climate Variability and Change*, J. Salinger, M.V.K. Sivakumar, and R.P. Motha, eds., Springer Netherlands, pp. 117–135.

[22] Olesen, J. E., and Bindi, M., 2002, “Consequences of Climate Change for European Agricultural Productivity, Land Use and Policy,” Eur. J. Agron., **16**(4), pp. 239–262.

[23] Olesen, J. E., Carter, T. R., Díaz-Ambrona, C. H., Fronzek, S., Heidmann, T., Hickler, T., Holt, T., Minguez, M. I., Morales, P., Palutikof, J. P., Quemada, M., Ruiz-Ramos, M., Rubæk, G. H., Sau, F., Smith, B., and Sykes, M. T., 2007, “Uncertainties in Projected Impacts of Climate Change on European Agriculture and Terrestrial Ecosystems Based on Scenarios from Regional Climate Models,” Clim. Change, **81**(1), pp. 123–143.

[24] Richter, G. M., and Semenov, M. A., 2005, “Modelling Impacts of Climate Change on Wheat Yields in England and Wales: Assessing Drought Risks,” Agric. Syst., **84**(1), pp. 77–97.

[25] Sivakumar, M. V. K., Das, H. P., and Brunini, O., 2005, “Impacts of Present and Future Climate Variability and Change on Agriculture and Forestry in the Arid and Semi-Arid Tropics,” Clim. Change, **70**(1–2), pp. 31–72.

[26] Tao, F., Yokozawa, M., Hayashi, Y., and Lin, E., 2003, “Future Climate Change, the Agricultural Water Cycle, and Agricultural Production in China,” Agric. Ecosyst. Environ., **95**(1), pp. 203–215.

[27] Cosgrove, E., 2017, “BREAKING: Vertical Farming Startup Plenty Acquires Bright Agrotech to Scale,” AgFunderNews [Online]. Available: https://agfundernews.com/breaking-vertical-farming-startup-plenty-acquires-bright-agrotech-scale.html. [Accessed: 18-Sep-2017].

[28] Ayres, R. U., 1995, “Life Cycle Analysis: A Critique,” Resour. Conserv. Recycl., **14**(3), pp. 199–223.

[29] USDA, 2016, “Life Cycle Assessment,” U. S. Dep. Agric. [Online]. Available: https://data.nal.usda.gov/life-cycle-assessment. [Accessed: 05-Sep-2016].

[30] Ozkan, B., Kurklu, A., and Akcaoz, H., 2004, “An Input–output Energy Analysis in Greenhouse Vegetable Production: A Case Study for Antalya Region of Turkey,” Biomass Bioenergy, **26**(1), pp. 89–95.

[31] Yaldiz, O. (Akdeniz U. F. of A., Ozturk, H. H., Zeren, Y., and Bascetincelik, A. (Cukurova U. F. of A., 1990, “Use of energy in the production of field crops in Turkey,” Akdeniz Univ. J. Fac. Agric. Turk.

[32] Singh, J. M., 2002, “On Farm Energy Use Pattern in Different Cropping Systems in Haryana, India,” Master Sci. Ger. Int. Inst. Manag. Univ. Flensbg.

[33] Heidari, M. D., and Omid, M., 2011, “Energy Use Patterns and Econometric Models of Major Greenhouse Vegetable Productions in Iran,” Energy, **36**(1), pp. 220–225.

[34] Yousefi, M., Darijani, F., and Alipour, A., 2012, “Comparing Energy Flow of Greenhouse and Open-Field Cucumber Production Systems in Iran (PDF Download Available).”

[35] Lages Barbosa, G., Almeida Gadelha, F. D., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M., and Halden, R. U., 2015, “Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods,” Int. J. Environ. Res. Public. Health, **12**(6), pp. 6879–6891.

[36] 2017, “Green Building Solutions,” Life Cycle Assess.

[37] Thomassen, M. A., van Calker, K. J., Smits, M. C., Iepema, G. L., and de Boer, I. J., 2008, “Life Cycle Assessment of Conventional and Organic Milk Production in the Netherlands,” Agric. Syst., **96**(1), pp. 95–107.

[38] Hospido, A., Moreira, M. T., and Feijoo, G., 2003, "Simplified Life Cycle Assessment of Galician Milk Production," Int. Dairy J., **13**(10), pp. 783–796.

[39] Flysjö, A., Cederberg, C., Henriksson, M., and Ledgard, S., 2011, "How Does Co-Product Handling Affect the Carbon Footprint of Milk? Case Study of Milk Production in New Zealand and Sweden," Int. J. Life Cycle Assess., **16**(5), pp. 420–430.

[40] De Boer, I. J., 2003, "Environmental Impact Assessment of Conventional and Organic Milk Production," Livest. Prod. Sci., **80**(1), pp. 69–77.

[41] Cederberg, C., and Stadig, M., 2003, "System Expansion and Allocation in Life Cycle Assessment of Milk and Beef Production," Int. J. Life Cycle Assess., **8**(6), pp. 350–356.

[42] Cederberg, C., and Mattsson, B., 2000, "Life Cycle Assessment of Milk Production—a Comparison of Conventional and Organic Farming," J. Clean. Prod., **8**(1), pp. 49–60.

[43] Cederberg, C., and Flysjö, A., 2004, "Life Cycle Inventory of 23 Dairy Farms in South-Western Sweden."

[44] Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M., and Pengue, W. A., 2008, "LCA of Soybean Meal," Int. J. Life Cycle Assess., **13**(3), p. 240.

[45] Mattsson, B., Cederberg, C., and Blix, L., 2000, "Agricultural Land Use in Life Cycle Assessment (LCA): Case Studies of Three Vegetable Oil Crops," J. Clean. Prod., **8**(4), pp. 283–292.

[46] Meisterling, K., Samaras, C., and Schweizer, V., 2009, "Decisions to Reduce Greenhouse Gases from Agriculture and Product Transport: LCA Case Study of Organic and Conventional Wheat," J. Clean. Prod., **17**(2), pp. 222–230.

[47] Fallahpour, F., Aminghafouri, A., Behbahani, A. G., and Bannayan, M., 2012, "The Environmental Impact Assessment of Wheat and Barley Production by Using Life Cycle Assessment (LCA) Methodology," Environ. Dev. Sustain., **14**(6), pp. 979–992.

[48] Wang, M., Xia, X., Zhang, Q., and Liu, J., 2010, "Life Cycle Assessment of a Rice Production System in Taihu Region, China," Int. J. Sustain. Dev. World Ecol., **17**(2), pp. 157–161.

[49] Hokazono, S., and Hayashi, K., 2012, "Variability in Environmental Impacts during Conversion from Conventional to Organic Farming: A Comparison among Three Rice Production Systems in Japan," J. Clean. Prod., **28**, pp. 101–112.

[50] Blengini, G. A., and Busto, M., 2009, "The Life Cycle of Rice: LCA of Alternative Agri-Food Chain Management Systems in Vercelli (Italy)," J. Environ. Manage., **90**(3), pp. 1512–1522.

[51] Point, E., Tyedmers, P., and Naugler, C., 2012, "Life Cycle Environmental Impacts of Wine Production and Consumption in Nova Scotia, Canada," J. Clean. Prod., **27**, pp. 11–20.

[52] Petti, L., Raggi, A., De Camillis, C., Matteucci, P., Sára, B., and Pagliuca, G., 2006, "Life Cycle Approach in an Organic Wine-Making Firm: An Italian Case-Study," *Proceedings Fifth Australian Conference on Life Cycle Assessment, Melbourne, Australia*, pp. 22–24.

[53] Notarnicola, B., Tassielli, G., and Nicoletti, G. M., 2003, "Life Cycle Assessment (LCA) of Wine Production," Environ.-Friendly Food Process., **306**, p. 326.

[54] Gazulla, C., Raugei, M., and Fullana-i-Palmer, P., 2010, "Taking a Life Cycle Look at Crianza Wine Production in Spain: Where Are the Bottlenecks?," Int. J. Life Cycle Assess., **15**(4), pp. 330–337.

[55] Aranda, A., Zabalza, I., and Scarpellini, S., 2005, "Economic and Environmental Analysis of the Wine Bottle Production in Spain by Means of Life Cycle Assessment," Int. J. Agric. Resour. Gov. Ecol., **4**(2), pp. 178–191.

[56] Pizzigallo, A. C. I., Granai, C., and Borsa, S., 2008, "The Joint Use of LCA and Emergy Evaluation for the Analysis of Two Italian Wine Farms," J. Environ. Manage., **86**(2), pp. 396–406.

[57] Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., and Shiina, T., 2009, "A Review of Life Cycle Assessment (LCA) on Some Food Products," J. Food Eng., **90**(1), pp. 1–10.

[58] Mattsson, B., 1999, "Environmental Life Cycle Assessment (LCA) of Agricultural Food Production."

[59] Deurer, M., Clothier, B., Huh, K.-Y., Jun, G.-I., Kim, I.-H., and Kim, D.-I., 2011, “Trends and Interpretation of Life Cycle Assessment (LCA) for Carbon Footprinting of Fruit Products: Focused on Kiwifruits in Gyeongnam Region,” Korean J. Hortic. Sci. Technol., **29**(5), pp. 389–406.
[60] Cerutti, A. K., Bruun, S., Beccaro, G. L., and Bounous, G., 2011, “A Review of Studies Applying Environmental Impact Assessment Methods on Fruit Production Systems,” J. Environ. Manage., **92**(10), pp. 2277–2286.
[61] i Canals, L. M., Burnip, G. M., and Cowell, S. J., 2006, “Evaluation of the Environmental Impacts of Apple Production Using Life Cycle Assessment (LCA): Case Study in New Zealand,” Agric. Ecosyst. Environ., **114**(2), pp. 226–238.
[62] i Canals, L. M., and Polo, G. C., 2003, “Life Cycle Assessment of Fruit Production,” Mattsson B Sonesson U Environ. Food Process. Woodhead Publ. Ltd. CRC Press LLC Camb. Boca Raton, pp. 29–53.
[63] i Canals, M., “L., Burnip GM and Cowell, SJ (2006). Evaluation of the Environmental Impacts of Apple Production Using Life Cycle Assessment (LCA): Case Study in New Zealand,” Agric. Ecosyst. Environ., **114**(2–4), pp. 226–238.
[64] Liu, Y., Langer, V., Høgh-Jensen, H., and Egelyng, H., 2010, “Life Cycle Assessment of Fossil Energy Use and Greenhouse Gas Emissions in Chinese Pear Production,” J. Clean. Prod., **18**(14), pp. 1423–1430.
[65] Mouron, P., Nemecek, T., Scholz, R. W., and Weber, O., 2006, “Management Influence on Environmental Impacts in an Apple Production System on Swiss Fruit Farms: Combining Life Cycle Assessment with Statistical Risk Assessment,” Agric. Ecosyst. Environ., **114**(2), pp. 311–322.
[66] Mouron, P., Scholz, R. W., Nemecek, T., and Weber, O., 2006, “Life Cycle Management on Swiss Fruit Farms: Relating Environmental and Income Indicators for Apple-Growing,” Ecol. Econ., **58**(3), pp. 561–578.
[67] Dorais, M., 2010, *Life Cycle Assessment Analyses of New Sustainable Greenhouse Growing Systems*, Agriculture and Agri-Food Canada, Laval University, Quebec.
[68] Sanyé-Mengual, E., Cerón-Palma, I., Oliver-Solà, J., and Montero, J. I., 2013, “Environmental Analysis of the Logistics of Agricultural Products from Roof Top Greenhouses in Mediterranean Urban Areas,” J. Sci. Food Agric., **93**(1), pp. 100–109.
[69] Bartzas, G., Zaharaki, D., and Komnitsas, K., 2015, “Life Cycle Assessment of Open Field and Greenhouse Cultivation of Lettuce and Barley,” Inf. Process. Agric., **2**(3–4), pp. 191–207.
[70] Muñoz, P., Antón, A., Nuñez, M., Paranjpe, A., Ariño, J., Castells, X., Montero, J. I., and Rieradevall, J., 2008, “COMPARING THE ENVIRONMENTAL IMPACTS OF GREENHOUSE VERSUS OPEN-FIELD TOMATO PRODUCTION IN THE MEDITERRANEAN REGION,” Acta Hortic., (801), pp. 1591–1596.
[71] Dorais, M., Antón, A., Montero, J. I., and Torrellas, M., 2014, “ENVIRONMENTAL ASSESSMENT OF DEMARCATED BED-GROWN ORGANIC GREENHOUSE TOMATOES USING RENEWABLE ENERGY,” Acta Hortic., (1041), pp. 291–298.
[72] Nordenström, E., Guest, G., and Fröling, M., 2010, “LCA OF LOCAL BIO-CHP FUELLED GREENHOUSES VERSUS MEDITERRANEAN OPEN FIELD TOMATOES FOR CONSUMPTION IN NORTHERN SCANDINAVIA,” *ECO-TECH´10, 22-24 November 2010, Kalmar, Sweden*, ECO-TECH´10, 22-24 November 2010, Kalmar, Sweden.
[73] NSW Department of Primary Industries, 2016, “Types of Greenhouses” [Online]. Available: http://www.dpi.nsw.gov.au/content/agriculture/horticulture/greenhouse/structures/types. [Accessed: 21-Jul-2016].
[74] Vadiee, A., and Martin, V., 2012, “Thermal Energy Storage Strategies for Effective Closed Greenhouse Design,” Appl. Energy [Online]. Available:

http://www.sciencedirect.com/science/article/pii/S0306261912009567. [Accessed: 24-Jun-2016].

[75] Cruickshanks, F., 2006, “Energy Storage Applications in Closed Greenhouses” [Online]. Available: http://www.iea-eces.org/files/concept_presentation_closed_greenhouses_fin_1.pdf. [Accessed: 15-Jul-2016].

[76] Schmidt, D., 2008, “GEO-THERMAL HEATING AND COOLING IN ‘CLOSED GREENHOUSE’ CONCEPT,” Greenh. Can. [Online]. Available: http://www.greenhousecanada.com/structures-equipment/heating/geo-thermal-heating-and-cooling-in-closed-greenhouse-concept-948. [Accessed: 15-Jul-2016].

[77] Kristinsson, J., 2006, “The Energy-Producing Greenhouse” [Online]. Available: http://www.unige.ch/cuepe/html/plea2006/Vol1/PLEA2006_PAPER112.pdf. [Accessed: 15-Jul-2016].

[78] Voogt, J., and van Weel, P., 2008, “CLIMATE CONTROL BASED ON STOMATAL BEHAVIOR IN A SEMI-CLOSED GREENHOUSE SYSTEM ‘AIRCOKAS,’” Acta Hortic., (797), pp. 151–156.

[79] van ¿t Ooster, A., van Henten, E. J., Janssen, E. G. O. N., Bot, G. P. A., and Dekker, E., 2008, “DEVELOPMENT OF CONCEPTS FOR A ZERO-FOSSIL-ENERGY GREENHOUSE,” Acta Hortic., (801), pp. 725–732.

[80] Heuvelink, E., Bakker, M., Marcelis, L. F. M., and Raaphorst, M., 2008, “CLIMATE AND YIELD IN A CLOSED GREENHOUSE,” Acta Hortic., (801), pp. 1083–1092.

[81] Opdam, J. J. ., Schoonderbeek, G. G., Heller, E. M. B., and de Gelder, A., 2005, “CLOSED GREENHOUSE: A STARTING POINT FOR SUSTAINABLE ENTREPRENEURSHIP IN HORTICULTURE,” Acta Hortic., (691), pp. 517–524.

[82] de Zwart, H. F., 2008, “OVERALL ENERGY ANALYSIS OF (SEMI) CLOSED GREENHOUSES,” Acta Hortic., (801), pp. 811–818.

[83] Speetjens, S. L., van der Walle, T., van Straten, G., Stigter, J. D., Janssen, H. J. J., and Gieling, T. H., 2005, “WATERGY, TOWARDS A CLOSED GREENHOUSE IN SEMI-ARID REGIONS - EXPERIMENT WITH A HEAT EXCHANGER,” Acta Hortic., (691), pp. 845–852.

[84] Hoes, H., Desmedt, J., Goen, K., and Wittemans, L., 2008, “THE GESKAS PROJECT, CLOSED GREENHOUSE AS ENERGY SOURCE AND OPTIMAL GROWING ENVIRONMENT,” Acta Hortic., (801), pp. 1355–1362.

[85] Vadiee, A., and Martin, V., 2012, “Energy Management in Horticultural Applications through the Closed Greenhouse Concept, State of the Art,” Renew. Sustain. Energy Rev., **16**(7), pp. 5087–5100.

[86] Tanny, J., Cohen, S., Grava, A., and Haijun, L., 2006, “AIRFLOW AND TURBULENCE IN A BANANA SCREENHOUSE,” Acta Hortic., (719), pp. 623–630.

[87] Giacomelli, G., Castilla, N., Henten, E. J. V., Mears, D., and Sase, S., 2007, “Innovation in Greenhouse Engineering” [Online]. Available: http://www.actahort.org/members/showpdf?session=26906. [Accessed: 22-Jul-2016].

[88] Moller, M., Tanny, J., Cohen, S., and Teitel, M., 2003, “Micrometeorological Characterisation in a Screenhouse,” Acta Hortic.

[89] Santos, B., Rios, D., and Nazco, R., 2006, “Climatic Conditions in Tomato Screenhouses in Tenerife (Canary Islands),” Acta Hortic.

[90] Fatnassi, H., Boulard, T., Poncet, C., and Chave, M., 2006, “Optimisation of Greenhouse Insect Screening with Computational Fluid Dynamics,” Biosyst. Eng., **93**(3), pp. 301–312.

[91] Raya, V., Parra, M., and Cid, M. C., 2006, “INFLUENCE OF CHANGES IN COVER AND HEIGHT ON THE CLIMATE OF CANARY-SCREENHOUSES FOR TOMATO GROWTH: PRELIMINARY RESULTS,” Acta Hortic., (719), pp. 535–542.

[92] Nelson, P. V., 2012, *Greenhouse Operation and Management*.

[93] Gonda, L., and Cugnasca, C., 2006, "A Proposal of Greenhouse Control Using Wireless Sensor Networks," ResearchGate [Online]. Available: https://www.researchgate.net/publication/271437945_A_Proposal_of_Greenhouse_Control_Using_Wireless_Sensor_Networks. [Accessed: 04-May-2017].

[94] J. Rader, D. Handeen, and V. Singh, 2013, "Cold-Climate Greenhouse Resource A Guidebook for Designing and Building a Cold-Climate Greenhouse" [Online]. Available: http://www.cura.umn.edu/sites/cura.advantagelabs.com/files/publications/CAP-186.pdf. [Accessed: 20-Jun-2016].

[95] Sanford, S., 2011, *Reducing Greenhouse Energy Consumption: An Overview*, A3907-01, University of Wisconsin.

[96] Rorabaugh, P., Jensen, M., and Giacomelli, G. A., 2002, *Introduction to Controlled Environment Agriculture and Hydroponics*, University of Arizonia, Campus Agricultural Center.

[97] Rader, J., Handeen, D., and Singh, V., "Cold-Climate Greenhouse Resource A Guidebook for Designing and Building a Cold-Climate Greenhouse."

[98] Hemming, S., Dueck, T., Janse, J., and van Noort, F., 2007, "The Effect of Diffuse Light on Crops," *International Symposium on High Technology for Greenhouse System Management: Greensys2007 801*, pp. 1293–1300.

[99] Gale, J., Levi, S., Feuermann, D., and Koppel, R., 1996, "LIQUID RADIATION FILTER GREENHOUSES (LRFGS) AND THEIR USE OF LOW QUALITY HOT AND COLD WATER, FOR HEATING AND COOLING" [Online]. Available: http://www.actahort.org/members/showpdf?session=2429. [Accessed: 24-Jun-2016].

[100] Oren-Shamir, M., Gussakovsky, E., Eugene, E., Nissim-Levi, A., Ratner, K., Ovadia, R., Giller, Y., and Shahak, Y., 2001, "Coloured Shade Nets Can Improve the Yield and Quality of Green Decorative Branches of *Pittosporum Variegatum*," J. Hortic. Sci. Biotechnol., **76**(3), pp. 353–361.

[101] Romacho, I., Hita, O., Soriano, T., Morales, M. I., Escobar, I., Suarez-Rey, E. M., Hernandez, J., and Castilla, N., 2006, "THE GROWTH AND YIELD OF CHERRY TOMATOES IN NET COVERED GREENHOUSES," Acta Hortic., (719), pp. 529–534.

[102] Castellano, S., Candura, A., and Scarascia Mugnozza, G., 2008, "RELATIONSHIP BETWEEN SOLIDITY RATIO, COLOUR AND SHADING EFFECT OF AGRICULTURAL NETS," Acta Hortic., (801), pp. 253–258.

[103] 2013, *Energy Conservation Initiative Project Summary Guterman Greenhouse, Facility 1068, 1068B*, Cornell University.

[104] Van Beveren, P. J. M., Bontsema, J., Van Straten, G., and Van Henten, E. J., 2015, "Minimal Heating and Cooling in a Modern Rose Greenhouse," Appl. Energy, **137**, pp. 97–109.

[105] van Ieperen, W., and Trouwborst, G., 2008, "THE APPLICATION OF LEDS AS ASSIMILATION LIGHT SOURCE IN GREENHOUSE HORTICULTURE: A SIMULATION STUDY," Acta Hortic., (801), pp. 1407–1414.

[106] Singh, D., Basu, C., Meinhardt-Wollweber, M., and Roth, B., 2015, "LEDs for Energy Efficient Greenhouse Lighting," Renew. Sustain. Energy Rev., **49**, pp. 139–147.

[107] Nelson, J. A., and Bugbee, B., 2014, "Economic Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures," PLOS ONE, **9**(6), p. e99010.

[108] Caldwell, M. M., 1971, "Solar UV Irradiation and the Growth and Development of Higher Plants," Photophysiology, **6**, pp. 131–177.

[109] Massa, G. D., Kim, H.-H., Wheeler, R. M., and Mitchell, C. A., 2008, "Plant Productivity in Response to LED Lighting," HortScience, **43**(7), pp. 1951–1956.

[110] Goins, G. D., Ruffe, L. M., Cranston, N. A., Yorio, N. C., Wheeler, R. M., and Sager, J. C., 2001, *Salad Crop Production under Different Wavelengths of Red Light-Emitting Diodes (LEDs)*, SAE Technical Paper.

[111] Goins, G. D., Yorio, N. C., Sanwo, M. M., and Brown, C. S., 1997, “Photomorphogenesis, Photosynthesis, and Seed Yield of Wheat Plants Grown under Red Light-Emitting Diodes (LEDs) with and without Supplemental Blue Lighting,” J. Exp. Bot., **48**(7), pp. 1407–1413.

[112] Hernández, R., and Kubota, C., 2016, “Physiological Responses of Cucumber Seedlings under Different Blue and Red Photon Flux Ratios Using LEDs,” Environ. Exp. Bot., **121**, pp. 66–74.

[113] Schuerger, A. C., Brown, C. S., and Stryjewski, E. C., 1997, “Anatomical Features of Pepper Plants (Capsicum Annuum L.) Grown under Red Light-Emitting Diodes Supplemented with Blue or Far-Red Light,” Ann. Bot., **79**(3), pp. 273–282.

[114] Folta, K. M., and Maruhnich, S. A., 2007, “Green Light: A Signal to Slow down or Stop,” J. Exp. Bot., **58**(12), pp. 3099–3111.

[115] Kim, H.-H., Goins, G. D., Wheeler, R. M., and Sager, J. C., 2004, “Green-Light Supplementation for Enhanced Lettuce Growth under Red-and Blue-Light-Emitting Diodes,” HortScience, **39**(7), pp. 1617–1622.

[116] Okamoto, K., Yanagi, T., and Kondo, S., 1996, “Growth and Morphogenesis of Lettuce Seedlings Raised under Different Combinations of Red and Blue Light,” *II Workshop on Environmental Regulation of Plant Morphogenesis 435*, pp. 149–158.

[117] Von Zabeltitz, C., 1994, “Climate Change Energy and the Environment Effective Use of Renewable Energies for Greenhouse Heating,” Renew. Energy, **5**(1), pp. 479–485.

[118] Sanford, S., 2009, “Choosing the Best Biomass Heating Option,” Greenh. Manag. [Online]. Available: http://www.greenhousemag.com/article/gm_1109_heating_sanford/. [Accessed: 22-Jul-2016].

[119] Menghini, S., Pfoestl, E., Marinelli, A., Bibbiani, C., Fantozzi, F., Gargari, C., Campiotti, C. A., Schettini, E., and Vox, G., 2016, “Florence ‘Sustainability of Well-Being International Forum’. 2015: Food for Sustainability and Not Just Food, FlorenceSWIF2015Wood Biomass as Sustainable Energy for Greenhouses Heating in Italy,” Agric. Agric. Sci. Procedia, **8**, pp. 637–645.

[120] Oladiran O. Fasina, Bransby, D., Sibley, J. and Gilliam, and C., 2006, “HEATING OF GREENHOUSE WITH BIOFUEL PELLETS,” American Society of Agricultural and Biological Engineers.

[121] Dion, L.-M., Lefsrud, M., and Orsat, V., 2011, “Review of CO2 Recovery Methods from the Exhaust Gas of Biomass Heating Systems for Safe Enrichment in Greenhouses,” Biomass Bioenergy, **35**(8), pp. 3422–3432.

[122] Joudi, K. A., and Farhan, A. A., 2014, “Greenhouse Heating by Solar Air Heaters on the Roof,” Renew. Energy, **72**, pp. 406–414.

[123] Ghosal, M. K., Tiwari, G. N., Das, D. K., and Pandey, K. P., 2004, “Modeling and Comparative Thermal Performance of Ground Air Collector and Earth Air Heat Exchanger for Heating of Greenhouse,” Energy Build., **37**(6), pp. 613–621.

[124] Denzer, A., Wang, L., Thomas, Y., and McMorrow, G., 2017, “Greenhouse Design with Waste Heat: Principles and Practices,” *AEI 2017*, pp. 440–455.

[125] Arzbaecher, C., Parmenter, K., and Fouche, E., 2007, “Industrial Waste-Heat Recovery: Benefits and Recent Advancements in Technology and Applications,” *Proceedings of the ACEEE*, pp. 2–1.

[126] Garton, R. R., and Christianson, A. G., 1970, “Beneficial Uses of Waste Heat- An Evaluation” [Online]. Available: http://nepis.epa.gov/Exe/ZyNET.exe/2000T7HM.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1991+Thru+1994&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C91thru94%5CTxt%5C00000016%5C2000T7HM.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Displ

ay=p%7Cf&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL#. [Accessed: 17-Jun-2016].

[127] Rotz, C. A., 1979, "Feasibility of Greenhouse Heating in Pennsylvania with Power Plant Waste Heat" [Online]. Available: https://www.researchgate.net/publication/269990480_Feasibility_of_Greenhouse_Heating_in_Pennsylvania_with_Power_Plant_Waste_Heat. [Accessed: 17-Jun-2016].

[128] Degelman, L., 1975, "A Weather Simulation Model for Building Energy Analysis" [Online]. Available: https://www.researchgate.net/publication/279649182_A_weather_simulation_model_for_building_energy_analysis. [Accessed: 18-Jul-2016].

[129] Dr. Ruhrmann, 1995, "CASE REPORTS ON RELEVANT MEASURES AND TECHNOLOGIES FOR IMPROVED ENERGY EFFICIENCY AND RENEWABLE ENERGY SOURCES IN GREENHOUSES – WITH A VIEW TO APPLICATIONS IN NORTHERN EUROPE."

[130] 2013, "Germany: RWE's Horti-Therm Plus Cooling Water Heats Greenhouses" [Online]. Available: http://www.hortidaily.com/article/3224/Germany-RWEs-Horti-Therm-Plus-cooling-water-heats-greenhouses. [Accessed: 18-Jul-2016].

[131] Walker, P. N., 1987, "Surface Heating Greenhouses with Power Plant Cooling Water" [Online]. Available: http://elibrary.asabe.org/azdez.asp?AID=35296&t=2. [Accessed: 17-Jun-2016].

[132] Burns, E. R., Pile, R. S., Madewell, C. E., and Carter, J., 1976, "Using Power Plant Discharge Water in Controlled Environment Greenhouses. Progress Report 2" [Online]. Available: https://www.researchgate.net/publication/236416305_Using_power_plant_discharge_water_in_controlled_environment_greenhouses_Progress_report_2. [Accessed: 18-Jul-2016].

[133] Pervilä, M., Remes, L., and Kangasharju, J., 2012, "Harvesting Heat in an Urban Greenhouse," ACM Press, p. 7.

[134] Bond, T. E., Thompson, J. F., and Hasek, R. F., 1985, "Reducing Energy Costs in California Greenhouses," Leafl. - Univ. Calif. Coop. Ext. Serv. USA.

[135] Sethi, V. P., and Sharma, S. K., 2007, "Survey of Cooling Technologies for Worldwide Agricultural Greenhouse Applications" [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0038092X07000771. [Accessed: 24-Jun-2016].

[136] Peña, A. ., Molina-Aiz, F. ., and Valera, D. L., 2005, "Optimisation of Almería-Type Greenhouse Ventilation Performance with Computational Fluid Dynamics" [Online]. Available: http://wwwlib.teiep.gr/images/stories/acta/Acta%20691/691_52.pdf. [Accessed: 10-Jul-2016].

[137] Villagrán, E. A., Gil, R., Acuña, J. F., and Bojacá, C. R., 2012, "Optimization of Ventilation and Its Effect on the Microclimate of a Colombian Multispan Greenhouse," Agron. Colomb., **30**(2), pp. 282–288.

[138] Baeza, E. J., Pérez-Parra, J., and Montero, J. I., 2004, "Effect of Ventilator Size on Natural Ventilation in Parral Greenhouse by Means of CFD Simulations," *International Conference on Sustainable Greenhouse Systems-Greensys2004 691*, pp. 465–472.

[139] Baeza, E. J., Pérez-Parra, J. J., Montero, J. I., Bailey, B. J., López, J. C., and Gázquez, J. C., 2009, "Analysis of the Role of Sidewall Vents on Buoyancy-Driven Natural Ventilation in Parral-Type Greenhouses with and without Insect Screens Using Computational Fluid Dynamics," Biosyst. Eng., **104**(1), pp. 86–96.

[140] Baeza, E. J., Pérez-Parra, J. J., Lopez, J. C., and Montero, J. I., 2006, "CFD Study of the Natural Ventilation Performance of a Parral Type Greenhouse with Different Numbers of Spans and Roof Vent Configurations," *International Symposium on Greenhouse Cooling 719*, pp. 333–340.

[141] Parra, J. P., 2002, "Ventilación Natural de Invernaderos Tipo Parral," Universidad de Córdoba.

[142] Sase, S., 2006, "AIR MOVEMENT AND CLIMATE UNIFORMITY IN VENTILATED GREENHOUSES," Acta Hortic., (719), pp. 313–324.

[143] Montero, J. I., Hunt, G. R., Kamaruddin, R., Antón, A., and Bailey, B. J., 2001, "Effect of Ventilator Configuration on Wind-Driven Ventilation in a Crop Protection Structure for the Tropics," J. Agric. Eng. Res., **80**(1), pp. 99–107.

[144] Nielsen, O. F., 2002, "Natural Ventilation of a Greenhouse with Top Screen," Biosyst. Eng., **81**(4), pp. 443–451.

[145] Montero, J. I., Stanghellini, C., and Castilla, N., 2009, "Greenhouse Technology for Sustainable Production in Mild Winter Climate Areas: Trends and Needs" [Online]. Available: http://www.actahort.org/members/showpdf?session=1208. [Accessed: 24-Jun-2016].

[146] Kacira, M., Sase, S., and Okushima, L., 2004, "Effects of Side Vents and Span Numbers on Wind-Induced Natural Ventilation of a Gothic Multi-Span Greenhouse," Jpn. Agric. Res. Q. JARQ, **38**(4), pp. 227–233.

[147] Mistriotis, A., Bot, G. P. A., Picuno, P., and Scarascia-Mugnozza, G., 1997, "Analysis of the Efficiency of Greenhouse Ventilation Using Computational Fluid Dynamics," Agric. For. Meteorol., **85**(3), pp. 217–228.

[148] Reichrath, S., and Davies, T. W., 2002, "Using CFD to Model the Internal Climate of Greenhouses: Past, Present and Future," Agronomie, **22**(1), pp. 3–19.

[149] C. Kittas, T. Bartzanas, and A. Jaffrin, 2001, "GREENHOUSE EVAPORATIVE COOLING: MEASUREMENT AND DATA ANALYSIS," Trans. ASAE, **44**(3).

[150] Sabeh, N. C., Giacomelli, G. A., and Kubota, C., 2006, "Water Use for Pad and Fan Evaporative Cooling of a Greenhouse in a Semi-Arid Climate."

[151] Bucklin, R. A. (University of F.), Henley, R. W., and McConnell, D. B., 1993, "Fan and Pad Greenhouse Evaporative Cooling Systems," Circ. Fla. Coop. Ext. Serv. USA.

[152] Jain, D., and Tiwari, G. N., 2002, "Modeling and Optimal Design of Evaporative Cooling System in Controlled Environment Greenhouse," Energy Convers. Manag., **43**(16), pp. 2235–2250.

[153] Arbel, A., Yekutieli, O., and Barak, M., 1999, "Performance of a Fog System for Cooling Greenhouses," J. Agric. Eng. Res., **72**(2), pp. 129–136.

[154] Abdel-Ghany, A. M., and Kozai, T., 2006, "Dynamic Modeling of the Environment in a Naturally Ventilated, Fog-Cooled Greenhouse," Renew. Energy, **31**(10), pp. 1521–1539.

[155] Giacomelli, G. A., Giniger, M. S., Krass, A. E., and Mears, D. R., 1985, "IMPROVED METHODS OF GREENHOUSE EVAPORATIVE COOLING," Acta Hortic., (174), pp. 49–56.

[156] Feuermann, D. (Ben-G. U. of the N., Kopel, R., Zeroni, M., Levi, S., and Gale, J., 1997, "Theory and Validation of a Liquid Radiation Filter Greenhouse Simulation for Performance Prediction," Trans. ASAE USA.

[157] Feuermann, D., Kopel, R., Zeroni, M., Levi, S., and Gale, J., 1998, "Evaluation of a Liquid Radiation Filter Greenhouse in a Desert Environment," Trans. ASAE, **41**(6), p. 1781.

[158] Canham, A. E., 1962, "Shading Glasshouses with Liquid Films. A Preliminary Report." [Online]. Available: https://www.cabdirect.org/cabdirect/abstract/19630304376. [Accessed: 14-Jul-2016].

[159] Gale, J., and Zeroni, M., 1984, *Cultivation of Plants in Brackish Water in Controlled Environment Agriculture.*

[160] Abdel-Ghany, A. M., Kozai, T., Kubota, C., and Taha, I. S., 2001, "Investigation of the Spectral Optical Properties of the Liquid Radiation Filters for Using in the Greenhouse Applications," J. Agric. Meteorol., **57**(1), pp. 11–19.

[161] Chiapale, J.-P., Van Bavel, C. H. M., and Sadler, E. J., 1983, "Comparison of Calculated and Measured Performance of a Fluid-Roof and a Standard Greenhouse," Energy Agric., **2**, pp. 75–89.

[162] Pollock, R., Adelberg, J. W., Fox, C., and Bonaca, G., 2002, *Apparatus and System for Plant Production*, Google Patents.

[163] Sadler, E. J., and Van Bavel, C. H. M., 1984, “Simulation and Measurement of Energy Partition in a Fluid-Roof Greenhouse,” Agric. For. Meteorol., **33**(1), pp. 1–13.

[164] Van Bavel, C. H. M., and Damagnez, J., 1977, “A Simulation Model for Energy Storage and Savings of a Fluid-Roof Solar Greenhouse,” *Symposium on More Profitable Use of Energy in Protected Cultivation 76*, pp. 229–236.

[165] Kozai, T., 2001, “Plastic Films vs Fluid-Roof Cover for a Greenhouse in a Hot Climate: A Comparative Study by Simulation.,” 植物工場学会誌, **13**(4), pp. 237–246.

[166] Choi, J. M., Park, Y.-J., and Kang, S.-H., 2014, “Temperature Distribution and Performance of Ground-Coupled Multi-Heat Pump Systems for a Greenhouse,” Renew. Energy, **65**, pp. 49–55.

[167] Ozgener, O., and Hepbasli, A., 2005, “Experimental Investigation of the Performance of a Solar-Assisted Ground-Source Heat Pump System for Greenhouse Heating,” Int. J. Energy Res., **29**(3), pp. 217–231.

[168] Ozgener, O., and Hepbasli, A., 2005, “Exergoeconomic Analysis of a Solar Assisted Ground-Source Heat Pump Greenhouse Heating System,” Appl. Therm. Eng., **25**(10), pp. 1459–1471.

[169] Benli, H., 2011, “Energetic Performance Analysis of a Ground-Source Heat Pump System with Latent Heat Storage for a Greenhouse Heating,” Energy Convers. Manag., **52**(1), pp. 581–589.

[170] Santamouris, M., Balaras, C. A., Dascalaki, E., and Vallindras, M., 1994, “Passive Solar Agricultural Greenhouses: A Worldwide Classification and Evaluation of Technologies and Systems Used for Heating Purposes,” Sol. Energy, **53**(5), pp. 411–426.

[171] Santamouris, M., Argiriou, A., and Vallindras, M., 1994, “Design and Operation of a Low Energy Consumption Passive Solar Agricultural Greenhouse,” Sol. Energy, **52**(5), pp. 371–378.

[172] Roberts, W. J., 1997, *Environmnetal Control in Greenhouses.*, Cook College, Rutgers University, Center for Controlled Environment Agriculture.

[173] Roberts, W. J., Mears, D. R., and James, M. F., 1981, “FLOOR HEATING OF GREENHOUSES,” Acta Hortic., (115), pp. 259–268.

[174] T. Takakura, T. O. Manning, G. A. Giacomelli, and W. J. Roberts, 1994, “Feedforward Control for a Floor Heat Greenhouse,” Trans. ASAE, **37**(3), pp. 939–945.

[175] Puri, V. M., 1982, “Greenhouse Floor Heating System Optimization Using Long-Term Thermal Performance Design Curves,” Sol. Energy, **28**(6), pp. 469–481.

[176] Reiss, E., Mears, D. R., Manning, T. O., Wulster, G. J., and Both, A. J., 2007, “Numerical Modeling of Greenhouse Floor Heating,” Trans. ASABE, **50**(1), pp. 275–284.

[177] Li, C., Wang, H., Miao, H., and Ye, B., 2017, “The Economic and Social Performance of Integrated Photovoltaic and Agricultural Greenhouses Systems: Case Study in China,” Appl. Energy, **190**, pp. 204–212.

[178] Cossu, M., Murgia, L., Ledda, L., Deligios, P. A., Sirigu, A., Chessa, F., and Pazzona, A., 2014, “Solar Radiation Distribution inside a Greenhouse with South-Oriented Photovoltaic Roofs and Effects on Crop Productivity,” Appl. Energy, **133**, pp. 89–100.

[179] Yano, A., Kadowaki, M., Furue, A., Tamaki, N., Tanaka, T., Hiraki, E., Kato, Y., Ishizu, F., and Noda, S., 2010, “Shading and Electrical Features of a Photovoltaic Array Mounted inside the Roof of an East–west Oriented Greenhouse,” Biosyst. Eng., **106**(4), pp. 367–377.

[180] Yıldız, A., Ozgener, O., and Ozgener, L., 2012, “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,” Renew. Energy, **44**, pp. 281–287.

[181] Ureña-Sánchez, R., Callejón-Ferre, Á. J., Pérez-Alonso, J., and Carreño-Ortega, Á., 2012, “Greenhouse Tomato Production with Electricity Generation by Roof-Mounted Flexible Solar Panels,” Sci. Agric., **69**(4), pp. 233–239.

[182] Carlini, M., Honorati, T., and Castellucci, S., 2012, “Photovoltaic Greenhouses: Comparison of Optical and Thermal Behaviour for Energy Savings,” Math. Probl. Eng., **2012**, p. e743764.

[183] Castellano, S., 2014, “Photovoltaic Greenhouses: Evaluation of Shading Effect and Its Influence on Agricultural Performances,” J. Agric. Eng., **45**(4), pp. 168–175.

[184] Hussain, I., Ali, A., and Lee, G. H., 2015, “Performance and Economic Analyses of Linear and Spot Fresnel Lens Solar Collectors Used for Greenhouse Heating in South Korea,” Energy, **90**, **Part 2**, pp. 1522–1531.

[185] Cossu, M., Yano, A., Li, Z., Onoe, M., Nakamura, H., Matsumoto, T., and Nakata, J., 2016, “Advances on the Semi-Transparent Modules Based on Micro Solar Cells: First Integration in a Greenhouse System,” Appl. Energy, **162**, pp. 1042–1051.

[186] Lamnatou, C., and Chemisana, D., 2013, “Solar Radiation Manipulations and Their Role in Greenhouse Claddings: Fluorescent Solar Concentrators, Photoselective and Other Materials,” Renew. Sustain. Energy Rev., **27**, pp. 175–190.

[187] Lamnatou, C., and Chemisana, D., 2013, “Solar Radiation Manipulations and Their Role in Greenhouse Claddings: Fresnel Lenses, NIR- and UV-Blocking Materials,” Renew. Sustain. Energy Rev., **18**, pp. 271–287.

[188] Nayak, S., and Tiwari, G. N., 2008, “Energy and Exergy Analysis of Photovoltaic/Thermal Integrated with a Solar Greenhouse,” Energy Build., **40**(11), pp. 2015–2021.

[189] Nayak, S., and Tiwari, G. N., 2009, “Theoretical Performance Assessment of an Integrated Photovoltaic and Earth Air Heat Exchanger Greenhouse Using Energy and Exergy Analysis Methods,” Energy Build., **41**(8), pp. 888–896.

[190] Nayak, S., and Tiwari, G. N., 2010, “Energy Metrics of Photovoltaic/Thermal and Earth Air Heat Exchanger Integrated Greenhouse for Different Climatic Conditions of India,” Appl. Energy, **87**(10), pp. 2984–2993.

[191] Sonneveld, P. J., Swinkels, G. L. A. M., Campen, J., van Tuijl, B. A. J., Janssen, H. J. J., and Bot, G. P. A., 2010, “Performance Results of a Solar Greenhouse Combining Electrical and Thermal Energy Production,” Biosyst. Eng., **106**(1), pp. 48–57.

[192] Sonneveld, P. J., Swinkels, G. L. A. M., Bot, G. P. A., and Flamand, G., 2010, “Feasibility Study for Combining Cooling and High Grade Energy Production in a Solar Greenhouse,” Biosyst. Eng., **105**(1), pp. 51–58.

[193] Sonneveld, P. J., Swinkels, G. L. A. M., and Bot, G. P. A., 2009, “DESIGN OF A SOLAR GREENHOUSE WITH ENERGY DELIVERY BY THE CONVERSION OF NEAR INFRARED RADIATION - PART 1 OPTICS AND PV-CELLS,” Acta Hortic., (807), pp. 47–54.

[194] Sonneveld, P. J., Swinkels, G. L. A. M., Kempkes, F., Campen, J. B., and Bot, G. P. A., 2006, “GREENHOUSE WITH AN INTEGRATED NIR FILTER AND A SOLAR COOLING SYSTEM,” Acta Hortic., (719), pp. 123–130.

[195] Ganguly, A., Misra, D., and Ghosh, S., 2010, “Modeling and Analysis of Solar Photovoltaic-Electrolyzer-Fuel Cell Hybrid Power System Integrated with a Floriculture Greenhouse,” Energy Build., **42**(11), pp. 2036–2043.

[196] Wheeler, E., and Both, A. J., 2002, *Evaluating Greenhouse Mechanical Ventilation System Performance*, State University of New Jersey, New Jersey Agricultural Experiment Station, Rutgers.

[197] Vox, G., Teitel, M., Pardossi, A., Minuto, A., Tinivella, F., and Schettini, E., 2010, “Sustainable Greenhouse Systems,” Sustain. Agric. Technol. Plan. Manag. Nova Sci. Publ. Inc N. Y. NY USA, pp. 1–79.

[198] Adams, S. R., 2006, “The Physiology of Flowering: Quantifying the Effects of Photo-Thermal Environment,” *III International Symposium on Models for Plant Growth, Environmental Control and Farm Management in Protected Cultivation 718*, pp. 557–566.

[199] Van Henten, E. J., and Bontsema, J., 2007, “Open-Loop Optimal Temperature Control in Greenhouses,” *International Symposium on High Technology for Greenhouse System Management: Greensys2007 801*, pp. 629–636.

[200] Körner, O., and Challa, H., 2003, “Design for an Improved Temperature Integration Concept in Greenhouse Cultivation,” Comput. Electron. Agric., **39**(1), pp. 39–59.

[201] Körner, O., Bakker, M. J., and Heuvelink, E., 2004, “Daily Temperature Integration: A Simulation Study to Quantify Energy Consumption,” Biosyst. Eng., **87**(3), pp. 333–343.

[202] Körner, O., and Van Straten, G., 2008, “Decision Support for Dynamic Greenhouse Climate Control Strategies,” Comput. Electron. Agric., **60**(1), pp. 18–30.

[203] Rijsdijk, A. A., and Vogelezang, J. V. M., 2000, “TEMPERATURE INTEGRATION ON A 24-HOUR BASE: A MORE EFFICIENT CLIMATE CONTROL STRATEGY,” Acta Hortic., (519), pp. 163–170.

[204] Pressman, E., Shaked, R., and Firon, N., 2006, “Exposing Pepper Plants to High Day Temperatures Prevents the Adverse Low Night Temperature Symptoms,” Physiol. Plant., **126**(4), pp. 618–626.

[205] Spanomitsios, G. K., 2001, “Temperature Control and Energy Conservation in a Plastic Greenhouse,” J. Agric. Eng. Res., **80**(3), pp. 251–259.

[206] Wahid, A., Gelani, S., Ashraf, M., and Foolad, M. R., 2007, “Heat Tolerance in Plants: An Overview,” Environ. Exp. Bot., **61**(3), pp. 199–223.

[207] Campen, J. B., 2009, *Dehumidification of Greenhouses*.

[208] Körner, O., and Challa, H., 2003, “Process-Based Humidity Control Regime for Greenhouse Crops,” Comput. Electron. Agric., **39**(3), pp. 173–192.

[209] Jolliet, O., 1994, “HORTITRANS, a Model for Predicting and Optimizing Humidity and Transpiration in Greenhouses,” J. Agric. Eng. Res., **57**(1), pp. 23–37.

[210] 2017, “Carbon Dioxide In Greenhouses,” Minist. Agric. Food Rural Aff. [Online]. Available: http://www.omafra.gov.on.ca/english/crops/facts/00-077.htm. [Accessed: 21-Jul-2017].

[211] Baille, A., 2001, “TRENDS IN GREENHOUSE TECHNOLOGY FOR IMPROVED CLIMATE CONTROL IN MILD WINTER CLIMATES,” Acta Hortic., (559), pp. 161–168.

[212] Mortensen, L. M., 1987, “Review: CO2 Enrichment in Greenhouses. Crop Responses,” Sci. Hortic., **33**(1), pp. 1–25.

[213] van Berkel, N., 1984, “CO2 ENRICHMENT IN THE NETHERLANDS,” Acta Hortic., (162), pp. 197–206.

[214] Hicklenton, P. R., and others, 1988, *CO2 Enrichment in the Greenhouse. Principles and Practice.*, Timber Press.

[215] Chau, J., Sowlati, T., Sokhansanj, S., Preto, F., Melin, S., and Bi, X., 2009, “Techno-Economic Analysis of Wood Biomass Boilers for the Greenhouse Industry,” Appl. Energy, **86**(3), pp. 364–371.

[216] Dion, L.-M., Lefsrud, M., and Orsat, V., 2011, “Review of CO2 Recovery Methods from the Exhaust Gas of Biomass Heating Systems for Safe Enrichment in Greenhouses,” Biomass Bioenergy, **35**(8), pp. 3422–3432.

[217] Jaffrin, A., Bentounes, N., Joan, A. M., and Makhlouf, S., 2003, “Landfill Biogas for Heating Greenhouses and Providing Carbon Dioxide Supplement for Plant Growth,” Biosyst. Eng., **86**(1), pp. 113–123.

[218] Incrocci, L., Stanghellini, C., and Kempkes, F. L. K., 2008, “Carbon Dioxide Fertilization in Mediterranean Greenhouses: When and How Is It Economical?,” *International Symposium on Strategies Towards Sustainability of Protected Cultivation in Mild Winter Climate 807*, pp. 135–142.

[219] Nederhoff, E. M., 1989, “Technical Aspects, Management and Control of CO2 Enrichment in Greenhouses-Refereed Paper,” *IV International Symposium on CO2 in Protected Cultivation 268*, pp. 127–138.

[220] Kläring, H.-P., Hauschild, C., Heißner, A., and Bar-Yosef, B., 2007, "Model-Based Control of CO2 Concentration in Greenhouses at Ambient Levels Increases Cucumber Yield," Agric. For. Meteorol., **143**(3–4), pp. 208–216.

[221] López-Cruz, I. L., Fitz-Rodríguez, E., Torres-Monsivais, J. C., Trejo-Zúñiga, E. C., Ruíz-García, A., and Ramírez-Arias, A., 2014, "Control Strategies of Greenhouse Climate for Vegetables Production," *Biosystems Engineering: Biofactories for Food Production in the Century XXI*, Springer, pp. 401–421.

[222] Reece, C. F., 1996, "Evaluation of a Line Heat Dissipation Sensor for Measuring Soil Matric Potential," Soil Sci. Soc. Am. J., **60**(4), p. 1022.

[223] Flint, A. L., Campbell, G. S., Ellett, K. M., and Calissendorff, C., 2002, "Calibration and Temperature Correction of Heat Dissipation Matric Potential Sensors," Soil Sci. Soc. Am. J., **66**(5), p. 1439.

[224] Bontsema, J., and Stanghellini, C., 2007, "A Soft Sensor for on-Line Estimation of Ventilation of a Greenhouse."

[225] Janssen, H. J. J., Sarlikioti, V., Gieling, T. H., Meurs, E. J. J., Marcelis, L. F. M., and Ruijsch van Dugteren, J., 2008, "A PROTOTYPE SENSOR FOR ESTIMATING LIGHT INTERCEPTION BY PLANTS IN A GREENHOUSE," Acta Hortic., (801), pp. 621–628.

[226] Abdelaziz, M. E., Pokluda, R., and Paschold, P. J., 2009, "SENSITIVITY OF STEM DIAMETER VARIATIONS FOR DETECTING WATER STRESS IN TOMATO TRANSPLANTS," Acta Hortic., (807), pp. 189–194.

[227] Vermeulen, K., Steppe, K., Linh, N. S., Lemeur, R., De Backer, L., Bleyaert, P., Dekock, J., Aerts, J. M., and Berckmans, D., 2008, "SIMULTANEOUS RESPONSE OF STEM DIAMETER, SAP FLOW RATE AND LEAF TEMPERATURE OF TOMATO PLANTS TO DROUGHT STRESS," Acta Hortic., (801), pp. 1259–1266.

[228] Jansen, R., Hofstee, J. W., Verstappen, F., Bouwmeester, H., Posthumus, M., and van Henten, E., 2008, "A METHOD TO DETECT BASELINE EMISSION AND PLANT DAMAGE INDUCED VOLATILE EMISSION IN A GREENHOUSE," Acta Hortic., (801), pp. 1415–1422.

[229] Baek, M., Lee, M., Kim, H., Kim, T., Bae, N., Cho, Y., Park, J., and Shin, C., 2013, "A Novel Model for Greenhouse Control Architecture," *International Conference on Grid and Pervasive Computing*, Springer, pp. 262–269.

[230] Liu, H., Meng, Z., and Cui, S., 2007, "A Wireless Sensor Network Prototype for Environmental Monitoring in Greenhouses," *2007 International Conference on Wireless Communications, Networking and Mobile Computing*, pp. 2344–2347.

[231] Yoo, S. e, Kim, J. e, Kim, T., Ahn, S., Sung, J., and Kim, D., 2007, "A2S: Automated Agriculture System Based on WSN," *2007 IEEE International Symposium on Consumer Electronics*, pp. 1–5.

[232] Araki, M., 2009, "PID Control," Control Syst. Robot. Autom. Syst. Anal. Control Class. Approaches II Unbehauen HEd EOLSS Publ. Co Ltd Oxf. UK ISBN-13 9781848265912, pp. 58–79.

[233] Camacho, E. F., and Alba, C. B., 2013, *Model Predictive Control*, Springer Science & Business Media.

[234] El Ghoumari, M. Y., Tantau, H.-J., and Serrano, J., 2005, "Non-Linear Constrained MPC: Real-Time Implementation of Greenhouse Air Temperature Control," Comput. Electron. Agric., **49**(3), pp. 345–356.

[235] van Straten, G., Challa, H., and Buwalda, F., 2000, "Towards User Accepted Optimal Control of Greenhouse Climate," Comput. Electron. Agric., **26**(3), pp. 221–238.

[236] Aaslyng, J. M., Lund, J. B., Ehler, N., and Rosenqvist, E., 2003, "IntelliGrow: A Greenhouse Component-Based Climate Control System," Environ. Model. Softw., **18**(7), pp. 657–666.

[237] Aaslyng, J. M., Ehler, N., and Jakobsen, L., 2005, "Climate Control Software Integration with a Greenhouse Environmental Control Computer," Environ. Model. Softw., **20**(5), pp. 521–527.

[238] Piñón, S., Camacho, E. F., Kuchen, B., and Peña, M., 2005, “Constrained Predictive Control of a Greenhouse,” Comput. Electron. Agric., **49**(3), pp. 317–329.

[239] Blasco, X., Martínez, M., Herrero, J. M., Ramos, C., and Sanchis, J., 2007, “Model-Based Predictive Control of Greenhouse Climate for Reducing Energy and Water Consumption,” Comput. Electron. Agric., **55**(1), pp. 49–70.

[240] Chalabi, Z. S., Bailey, B. J., and Wilkinson, D. J., 1996, “A Real-Time Optimal Control Algorithm for Greenhouse Heating,” Comput. Electron. Agric., **15**(1), pp. 1–13.

[241] Seron, M., 2004, “Receding Horizon Control.”

[242] Tap, R. F., Van Willigenburg, L. G., and Van Straten, G., 1994, “Experimental Results of Receding Horizon Optimal Control of Greenhouse Climate,” *II IFAC/ISHS Workshop: Mathematical & Control Applications in Agriculture & Horticulture 406*, pp. 229–238.

[243] Van Straten, G., Van Willigenburg, L. G., and Tap, R. F., 2002, “The Significance of Crop Co-States for Receding Horizon Optimal Control of Greenhouse Climate,” Control Eng. Pract., **10**(6), pp. 625–632.

[244] Åström, K. J., and Wittenmark, B., 2013, *Adaptive Control: Second Edition*, Courier Corporation.

[245] Zeng, S., Hu, H., Xu, L., and Li, G., 2012, “Nonlinear Adaptive PID Control for Greenhouse Environment Based on RBF Network,” Sensors, **12**(5), pp. 5328–5348.

[246] Arvanitis, K. G., Paraskevopoulos, P. N., and Vernardos, A. A., 2000, “Multirate Adaptive Temperature Control of Greenhouses,” Comput. Electron. Agric., **26**(3), pp. 303–320.

[247] Pasgianos, G. D., Arvanitis, K. G., Polycarpou, P., and Sigrimis, N., 2003, “A Nonlinear Feedback Technique for Greenhouse Environmental Control,” Comput. Electron. Agric., **40**(1), pp. 153–177.

[248] Zhang, Z., 2008, “Multiobjective Optimization Immune Algorithm in Dynamic Environments and Its Application to Greenhouse Control,” Appl. Soft Comput., **8**(2), pp. 959–971.

[249] Hu, H., Xu, L., Wei, R., and Zhu, B., 2011, “Multi-Objective Control Optimization for Greenhouse Environment Using Evolutionary Algorithms,” Sensors, **11**(6), pp. 5792–5807.

[250] Babuska, R., and Mamdani, E., 2008, “Fuzzy Control,” Scholarpedia, **3**(2), p. 2103.

[251] Xu, Y.-H., Wu, W.-L., Xu, Y., Tham, M.-L., and Ramli, N., 2016, “A Framework of Fuzzy Control-Based Intelligent Control System for Greenhouse,” Artif. Intell. Res., **6**(1), p. 1.

[252] Lafont, F., and Balmat, J.-F., 2002, “Optimized Fuzzy Control of a Greenhouse,” Fuzzy Sets Syst., **128**(1), pp. 47–59.

[253] Salgado, P., and Cunha, J. B., 2005, “Greenhouse Climate Hierarchical Fuzzy Modelling,” Control Eng. Pract., **13**(5), pp. 613–628.

[254] Castañeda-Miranda, R., Ventura-Ramos, E., del Rocío Peniche-Vera, R., and Herrera-Ruiz, G., 2006, “Fuzzy Greenhouse Climate Control System Based on a Field Programmable Gate Array,” Biosyst. Eng., **94**(2), pp. 165–177.

[255] Trabelsi, A., Lafont, F., Kamoun, M., and Enea, G., 2007, “Fuzzy Identification of a Greenhouse,” Appl. Soft Comput., **7**(3), pp. 1092–1101.

[256] Fourati, F., and Chtourou, M., 2007, “A Greenhouse Control with Feed-Forward and Recurrent Neural Networks,” Simul. Model. Pract. Theory, **15**(8), pp. 1016–1028.

[257] Fourati, F., and Chtourou, M., 2011, “A Greenhouse Neural Control Using Generalized and Specialized Learning,” energy, **5**, p. 7.

[258] Du, L., 2009, “Expert Control Based on Neural Networks for Controlling Greenhouse Environment,” *Computer and Computing Technologies in Agriculture III*, Springer, Berlin, Heidelberg, pp. 126–132.

[259] Ferreira, P. M., Faria, E. A., and Ruano, A. E., 2002, “Neural Network Models in Greenhouse Air Temperature Prediction,” Neurocomputing, **43**(1), pp. 51–75.

[260] Frausto, H. U., and Pieters, J. G., 2004, “Modelling Greenhouse Temperature Using System Identification by Means of Neural Networks,” Neurocomputing, **56**, pp. 423–428.

[261] Linker, R., Seginer, I., and Gutman, P. O., 1998, “Optimal CO 2 Control in a Greenhouse Modeled with Neural Networks,” Comput. Electron. Agric., **19**(3), pp. 289–310.

[262] Patil, S. L., Tantau, H. J., and Salokhe, V. M., 2008, “Modelling of Tropical Greenhouse Temperature by Auto Regressive and Neural Network Models,” Biosyst. Eng., **99**(3), pp. 423–431.

[263] Seginer, I., Boulard, T., and Bailey, B. J., 1994, “Neural Network Models of the Greenhouse Climate,” J. Agric. Eng. Res., **59**(3), pp. 203–216.

[264] Seginer, I., 1997, “Some Artificial Neural Network Applications to Greenhouse Environmental Control,” Comput. Electron. Agric., **18**(2–3), pp. 167–186.

[265] Yousefi, M. R., Hasanzadeh, S., Mirinejad, H., and Ghasemian, M., 2010, “A Hybrid Neuro-Fuzzy Approach for Greenhouse Climate Modeling,” *Intelligent Systems (IS), 2010 5th IEEE International Conference*, IEEE, pp. 212–217.

[266] Coelho, J. P., de Moura Oliveira, P. B., and Cunha, J. B., 2005, “Greenhouse Air Temperature Predictive Control Using the Particle Swarm Optimisation Algorithm,” Comput. Electron. Agric., **49**(3), pp. 330–344.

[267] Setiawan, A., Albright, L. D., and Phelan, R. M., 2000, “Application of Pseudo-Derivative-Feedback Algorithm in Greenhouse Air Temperature Control,” Comput. Electron. Agric., **26**(3), pp. 283–302.

[268] Hill, J., 2006, “Dynamic Modeling Of Tree Growth And Energy Use In A Nursery Greenhouse Using Matlab And Simulink.”

[269] J. N. Walker, 1965, “Predicting Temperatures in Ventilated Greenhouses,” Trans. ASAE, **8**(3), pp. 0445–0448.

[270] Price, D. R., and Peart, R. M., 1973, “Simulation Model to Study the Utilization of Waste Heat Using a Combination Multiple Reservoir and Greenhouse Complex,” J. Environ. Qual., **2**(2), pp. 216–224.

[271] Chinese, D., Meneghetti, A., and Nardin, G., 2005, “Waste-to-Energy Based Greenhouse Heating: Exploring Viability Conditions through Optimisation Models,” Renew. Energy, **30**(10), pp. 1573–1586.

[272] Menghini, S., Pfoestl, E., Marinelli, A., Campiotti, C. A., Morosinotto, G., Puglisi, G., Schettini, E., and Vox, G., 2016, “Florence ‘Sustainability of Well-Being International Forum’. 2015: Food for Sustainability and Not Just Food, FlorenceSWIF2015Performance Evaluation of a Solar Cooling Plant Applied for Greenhouse Thermal Control,” Agric. Agric. Sci. Procedia, **8**, pp. 664–669.

[273] Ghosal, M. K., Tiwari, G. N., and Srivastava, N. S. L., 2003, “Thermal Modeling of a Greenhouse with an Integrated Earth to Air Heat Exchanger: An Experimental Validation” [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378778803001348. [Accessed: 24-Jun-2016].

[274] Ahamed, M. S., Guo, H., and Tanino, K., 2015, “A Pseudo Dynamic Model for Simulation of Greenhouse Energy Requirement.”

[275] Fuller, R. J., Meyer, C. P., and Sale, P. J. M., 1987, “Validation of a Dynamic Model for Predicting Energy Use in Greenhouses,” J. Agric. Eng. Res., **38**(1), pp. 1–14.

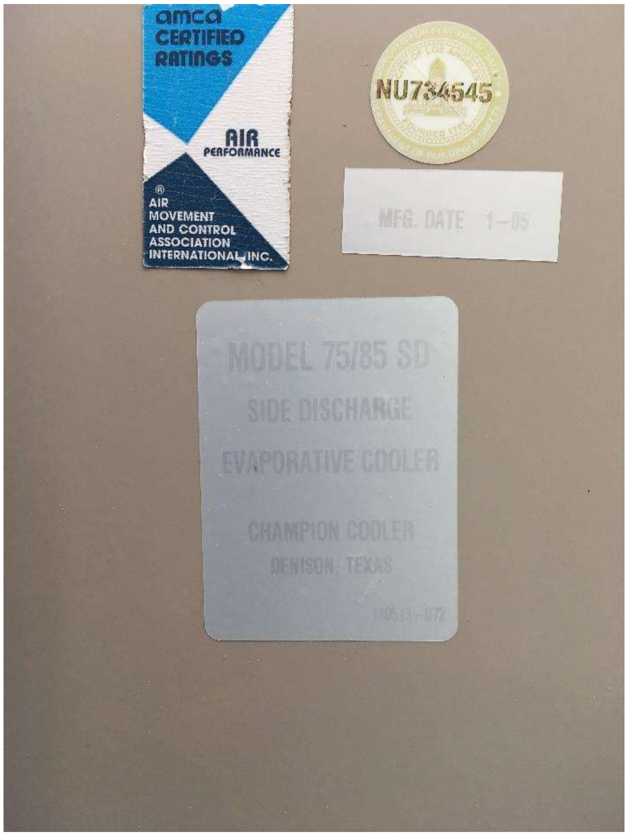
[276] Hollmuller, P., and Lachal, B., 1998, “TRNSYS Compatible Moist Air Hypocaust Model” [Online]. Available: https://www.researchgate.net/publication/265107066_TRNSYS_compatible_moist_air_hypocaust_model. [Accessed: 18-Jul-2016].

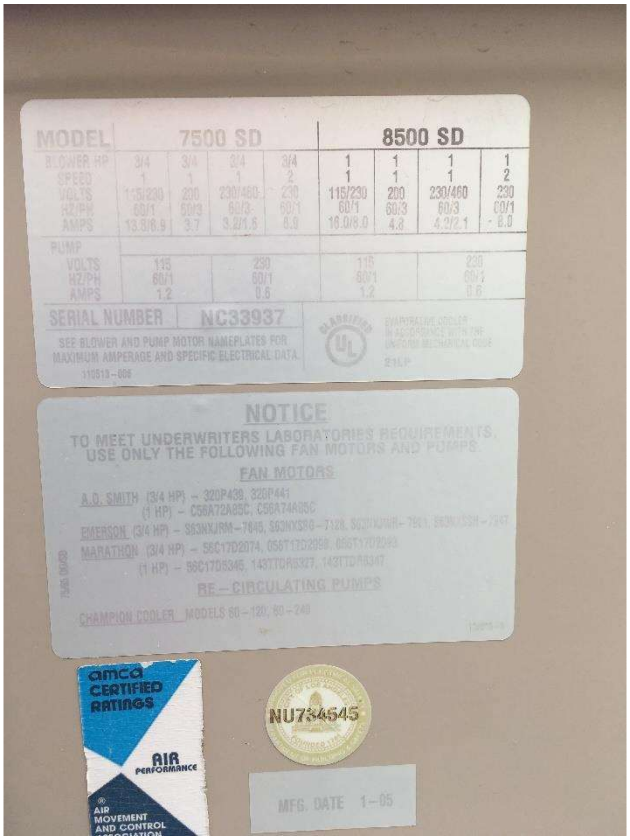
[277] Fitz-Rodríguez, E., Kubota, C., Giacomelli, G. A., Tignor, M. E., Wilson, S. B., and McMahon, M., 2010, “Dynamic Modeling and Simulation of Greenhouse Environments under Several Scenarios: A Web-Based Application,” Comput. Electron. Agric., **70**(1), pp. 105–116.

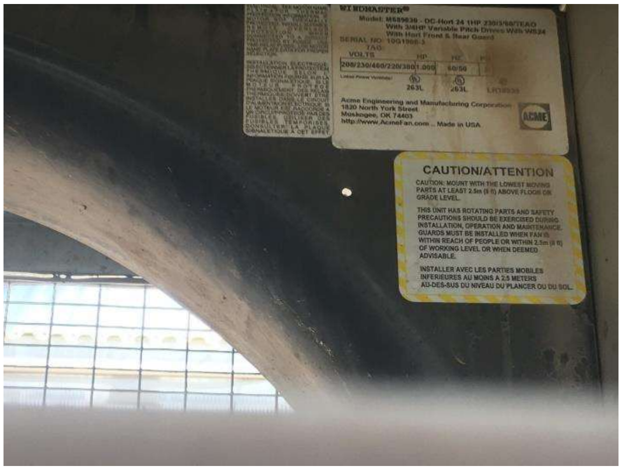
[278] “DATA SHEET SUNTUF_Long_US.pdf.”

[279] "Blower Door Basics," GreenBuildingAdvisor.com [Online]. Available: http://www.greenbuildingadvisor.com/blogs/dept/musings/blower-door-basics. [Accessed: 02-Dec-2017].

Appendix A


amca CERTIFIED RATINGS
AIR PERFORMANCE
AIR MOVEMENT AND CONTROL ASSOCIATION INTERNATIONAL, INC.
NU734545
MFG. DATE 1-05
MODEL 75/85 SD
SIDE DISCHARGE
EVAPORATIVE COOLER
CHAMPION COOLER
DENISON, TEXAS
110513-072


MODEL
7500 SD
8500 SD
BLOWER HP
SPEED
VOLTS
HZ/PH
AMPS
PUMP
SERIAL NUMBER
NC33937
SEE BLOWER AND PUMP MOTOR NAMEPLATES FOR MAXIMUM AMPERAGE AND SPECIFIC ELECTRICAL DATA.
NOTICE
TO MEET UNDERWRITERS LABORATORIES REQUIREMENTS, USE ONLY THE FOLLOWING FAN MOTORS AND PUMPS.
FAN MOTORS
A.O. SMITH
EMERSON
MARATHON
RE-CIRCULATING PUMPS
CHAMPION COOLER
amca CERTIFIED RATINGS
AIR PERFORMANCE
NU734545
MFG. DATE 1-05


WINDMASTER
Acme Engineering and Manufacturing Corporation
Muskogee, OK 74403
ACME
CAUTION/ATTENTION