SUPPLEMENTAL LIGHTING TIME BEST JUSTIFIES THE EFFICACY OF TRANSITION FROM HPS LIGHTING TO LED LIGHTING IN GREENHOUSE

by

MICHAEL ILARDI

(Under the Direction of Tom Lawrence)

ABSTRACT

A large portion of greenhouse overhead costs are attributed to the energy it takes to maintain an ideal growing environment, especially in climates where heating and supplemental lighting are a necessity. A lack of research on this topic leaves uncertainty about which variables to consider when justifying a change in supplemental lighting type. Using Engineering Equation Solver, nightly heating requirements were determined for a range of outdoor temperatures. This data was used in a MATLAB solver to calculate annual nightly heating contributions from High-Pressure Sodium (HPS) and LED lighting arrangements for different locations. Computational Fluid Dynamic analysis was performed to compare steady-state internal air temperatures for HPS and LED arrangements. It was found that HPS lamps contributed the most heat energy to the greenhouses. A measurable penalty was found for using LED lamps. Regression analysis revealed that the total lighting hours correlated most with the significance of this LED penalty.

INDEX WORDS: HPS (high-pressure sodium), LED (light emitting diode), Greenhouse, CEA (Controlled Environment Agriculture), Supplemental lighting, Heating, CFD (computational fluid dynamics), LED Penalty

AN EVALUATION OF THE ENERGY AND THERMAL IMPACTS OF A TRANSITION TO LED LIGHTING IN CONTROLLED ENVIRONMENT GREENHOUSES

by

MICHAEL ILARDI

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by

MICHAEL ILARDI

Major Professor: Tom Lawrence

Committee: A.J. Both
Ernest Tollner

Electronic Version Approved:

Ron Walcott
Vice Provost for Graduate Education and Dean of the Graduate School
The University of Georgia
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DEDICATION

This work is dedicated to my grandfather Oscar Easley who taught me that success comes from persistence and to always have fun along the way.

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CHAPTER 1

INTRODUCTION

Greenhouses, also known in the commercial horticulture industry as Controlled Environment Agriculture (CEA) facilities, are not a modern technology by any definition. Although modern greenhouses are much more advanced than those used in ancient times, the fundamental goal is exactly the same. Today, CEA is a much more viable industry allowing all types of fruits, vegetables, and flowers to be grown in even the harshest climates across the world. Because of this, CEA plays a very important role in not just commercial horticulture, but also for food production for many different areas of the world (Sanford, 2011). This is due to constant innovations in the industry and the complex climate control features that greenhouse operators and engineers have developed to ensure ideal growing conditions. To maintain a greenhouse properly, there are three main parameters that must be controlled in order to maintain adequate growing environments. These are lighting (from sun and supplemental sources), heating, and cooling. Often, these parameters are related in a way where adjustments to one parameter can cause a change in another.

Over the past decades, an increasing amount of research studies have been conducted with a focus on cost-effectiveness for heating, ventilation, and air conditioning (HVAC) applications in greenhouses (Brault et al, 1989) (Gómez et al, 2013) (Li and Willits, 2008) (Katzin et al, 2020) (Zhang et al, 2008). This research has opened up many new doors for innovations across the industry (Li and Willits 2008) and this trend has recently begun to involve the supplemental lighting industry. Grow lamps are evolving rapidly, especially with newer light-emitting diode (LED) technology. Much of this innovation is volatile, and research has been trying to keep up.

What is known is that high-pressure sodium (HPS) lamps are less energy efficient than LED lamps, and recent research has shown that the type of lamp used has an effect on the internal thermal environment of the greenhouse (Zhang et al, 2008) (Katzin et al, 2020). However, there are still questions regarding how specific climate conditions can impact the cost-effectiveness of a switch from HPS to LED lamps. The research study outlined here was conducted to enhance the understanding of the impacts of lighting choices on the energy consumption and thermal impacts within a typical commercial greenhouse. LED lamp manufacturers advertise all sorts of best-in-class performance metrics, meaning that the decision criteria used to switch from HPS lamps to LED lamps is not obvious. There needs to be a way to compare different systems based on independently verified information. In addition to this gap in knowledge, there is a very wide range of supplemental lighting needs that varies by outdoor radiation conditions. We know that heating and cooling loads are affected by climate conditions (Shamshiri & Ismail, 2013), but quantities of usable sunlight (Photosynthetically Active Radiation) can also vary, even within similar geographic locations. An in-depth study is needed to determine which parameters influence the effects that changes in supplemental lighting type have on heating load.

To provide adequate background information and to inform the reader of previously published research, a comprehensive literature review follows this introduction. The literature review presents the current knowledge that exists in the field and informs about the gap in published research that this study intends to fill. After the literature review, the methodology of this study is presented. Here, the approach to the problem and the plan that was implemented to solve it is discussed in detail. The methodology section also includes details about the different computational solvers that were used along with the justification for using these tools. The resulting findings are then presented followed by data analyses, interpretation, and applicable remarks. The conclusion section also offers recommendations based on the results of this study.

CHAPTER 2

LITERATURE REVIEW

List of Abbreviations

CEA – Controlled Environment Agriculture

LED – Light-Emitting Diode

HPS – High-Pressure Sodium

HVAC – Heating, ventilation, and air conditioning

CFD – Computational Fluid Dynamics

TMY – Typical Meteorological Year

DLI – Daily Lighting Integral

PAR – Photosynthetically-Active Radiation

PPFD – Photosynthetic Photon Flux Density

HDD – Heating Degree Days

Controlled Environment Agriculture

Controlled Environment Agriculture (CEA) facilities, also known as greenhouses, are used to create optimum growing conditions year-round crop production. They are commonly clad with glass, or rigid plastic on plastic film, which allows natural sunlight to reach the plant canopy while retaining some thermal energy that helps to maintain an optimal growing temperature. Greenhouses must maintain ideal growing conditions throughout the season, so most utilize heating and cooling systems in combination with supplemental lighting and shading systems to achieve the desired crop production (Albright & Brechner, 2011) (Katzin et al, 2020). Because CEA facilities create a microclimate that can be maintained year round, all kinds of vegetables, fruits, and horticultural plants can be produced and cultivated outside of their normal growing conditions (Sanford, 2011). Many foods are becoming more accessible in places they were once scarce or considered difficult to grow (Davies, 2005). Greenhouse food production is becoming increasingly more important in areas around the world that are experiencing rapid population growth, such as large, urban areas (Goodman & Minner 2019) (Altieri et al, 1999). The increasing demand on the greenhouses industry for high quality crop production presents several challenges for horticulture specialists, engineers, and other involved in greenhouse operations.

Ventilation and Air Circulation

Ventilation is an important means of controlling the internal airflow, humidity, CO_2 levels, and air temperature of a greenhouse. Each of these internal environmental parameters require control for maintaining a proper growing environment for plants (Chappell et al, 2011). Most of the energy from heat and humidity is transferred through and eventually out of a greenhouse by air. Therefore, airflow in and out of a greenhouse system is an important factor for maintaining an optimum plant growth environment (Zhang et al. 2016). According to Albright & Brechner (2011), proper ventilation is crucial to greenhouse operation because transpiration and photosynthetic rate are directly related to the amount of airflow. Improper ventilation and air conditioning design can lead to non-uniform airflow patterns which can cause several issues in crop production such as non-uniform crop growth, lower plant quality, and crop disorders (Zhang et al, 2016). Especially in hot or arid climates, effective ventilation is necessary to control internal temperatures as well as internal air circulation. These factors directly relate to natural convection effects within the greenhouse. Akrami et al. (2019) suggested using dehumidifiers (condensers) to control the humidity levels in regions with high ambient temperatures and humidity levels with low internal air circulation. They used Computational Fluid Dynamics (CFD) software to study the impact of different ventilation designs on improving air circulation in these stagnant areas. As is discussed further in the CFD section of the literature review, they found that they could increase the airflow in these regions by dehumidifiers to remove latent energy from the air, thus improving the air quality. This suggests that natural ventilation alone is not always satisfactory and other methods of improving air quality are required.

There are a few different methods of controlling the indoor temperature. Some industrial greenhouses make use of state-of-the-art automated ventilation systems to optimize natural ventilation. This involves the control of air vents via programs that optimize the air changeover rate within the greenhouse. These automation systems are common where the air is hot and humid, such as tropical climates and is often supplemented by other automation features (Shamshiri & Ismail, 2013). Some of these other features include shading and supplemental lighting (when necessary) via systems like LASSI, or “light and shade system implementation” (Albright & Brechner, 2011). These programs utilize data from forecasts to regulate the air inside the greenhouse for optimal growing conditions. Although these automated systems are intended to maximize natural ventilation, it is only effective for temperatures up to 27°C due to humidity and the trapping of heated air (such as under the canopy or in less aerodynamics portions of the greenhouse) that is not circulated by natural ventilation (Bartzanas et al, 2004) (Benni et al, 2019). When temperatures inside the greenhouse reach higher than 27°C, heat energy must removed from the air by other methods (Akrami et al, 2019), and natural ventilation is not as effective. Natural ventilation is also necessary for maintaining airflow that supports crop growth and prevent CO_2 build-up (Benni et al, 2019). If sufficient, natural ventilation via manually controlled vents is the preferred method of hot-air removal because automated systems have associated expenses. Fan ventilation (or mechanical ventilation) is commonly used to supplement natural ventilation as a method of increasing the airflow through a greenhouse. These systems use exhaust fans to increase the air changeover rate and have been found to lower temperatures within a typical sized greenhouse (100 meters and under) within 7°C of the outdoor temperature. However, this temperature gradient increases with the size of the greenhouse, and cooling becomes more reliant on roof ventilation (Flores-Velazquez et al, 2014).

Research has emerged which shows evidence of supplemental lighting adding measurable heat gain to greenhouses via radiation and convection, which puts a larger burden on ventilation systems when this heat is not needed (Ahamed et al, 2019) (Brault et al, 1989) (Katzin et al, 2020) (Yang et al, 2015). The costs associated with removing heat generated by energy inefficient lamp varieties are causing greenhouse operators to look towards alternatives. HPS lamps are being replaced with energy-efficient LED lamps as a cost-effective solution in climates where natural ventilation is desired method (Singh et al. 2015).

Heating

Greenhouse heating is one of the highest energy costs of many operations due to greenhouse structural materials being poor thermal insulators. In fact, it was measured that 20-40% of greenhouse energy lost can be due to the building envelope under certain conditions (Cuce et al, 2016). Historically, most research has been focused on innovative methods to reduce the costs associated with removing hot air from greenhouses (i.e., improvements in heating technology) – and until recently, there have not been many studies that research minimizing the impacts of greenhouse technologies that contribute to the heat input (Ahamed et al, 2019)) (Katzin et al, 2020). This new surge is due to newer technology that has allowed researchers to study the energy balance of a greenhouse internally. Most of these research studies utilize some method of computational, numerical method of physics concerning the greenhouse thermal environment. One such example is a 2017 study on energy optimization in greenhouses where a prediction model estimated that total energy consumption of a greenhouse accounts for between 50% and 90% of production costs, and in winter or colder climates, 50% of this energy consumption can be from space heating alone (Wang et al, 2006). Greenhouse heating demand varies widely by location and climate and many different methods are used such as heat pumps (geothermal or conventional), fuel powered unit-heaters/furnaces, or boilers to deliver hot water to the growing areas. Energy costs vary widely by location as well (Katzin et al, 2020). However, there is more involved in greenhouse heating than weather and climate. The type of supplemental lighting utilized by a greenhouse facility can also drastically affect space-heating load (Brault et al, 2019). Conventional HPS lamps, which are still widely used, can effectively serve as space-heaters due to their relatively low efficiency levels, and a study has recently shown that switching to more energy efficient lamps that produce less waste heat can subsequently cause heating costs to rise (Katzin et al, 2020).

Greenhouse operations in cold regions spend a lot of money on space heating to maintain optimal growing temperatures. For example, in Canada, heating costs make up 10-35% of total production costs (Ahamed et al. 2019). On average, heating is the most expensive energy cost in greenhouses, with estimates at around 65-85% of total energy costs (Runkle & Both, 2012). In warmer and more moderate climates, energy is also used to provide cooling in greenhouses, but cost impact on that tends to be small and is not the focus in this study. One method that greenhouse operators use to decrease heating costs is converting to energy efficient or renewable energy options. Some of these options include solar power and the use of ground source heat pumps, when used with energy storage systems or solar energy collectors, to maximize usage of "free" geothermal heating (Cuce et al, 2016). These energy efficient options are limited and are generally used to supplement more traditional fuels such as natural gas. Another option that greenhouse operations implement to reduce heating costs is by controlling the building envelope, such as by sealing locations where infiltration is found to occur. Automated ventilation control can be used to only ventilate when necessary and to prevent unnecessary heat loss.

Supplemental lighting, which is discussed in more depth in the next section, is one area that has not been thoroughly studied in its effect of contributing heat to the greenhouse thermal environment. Zhang et al. (1996) were one of the first to look into this with High-Intensity Discharge (HID) lamps. HID lamps include HPS and metal halide and are characterized by their usage of tungsten electrodes and ionized gas to produce light. It was found through a controlled study that HID lamps are capable of contributing up to 100% of the required heating when the outside temperature was around 10° - 12°C lower than the required interior temperature. This percentage dropped to 30% contributed to the required heating when the outdoor temperature was at least 25°C less than the indoor temperature (Zhang et al, 1996). The remaining percentage of the heating load in either case would need to be made up by the greenhouse heating system. Therefore, especially for cold climates, a heating system remains a necessity to supply the heating load under certain circumstances. LED lighting is a newer technology with a higher initial investment cost, but it also has a lower electrical lighting operating cost. However, there is limited research reported in the literature about the impact of LED lighting on the total greenhouse energy costs, particularly on the increase in heating demand.

In an industry with so much innovation to reduce energy usage and costs, this presents a challenge. Reducing lighting costs by implementing supplemental lighting with higher conversion efficiencies can increase the heating demand. Until recently, there was little information about how much this heating demand increased or how much lighting contributed to heating, although a study by Katzin et al. (2020) did look into this. They found that LED lighting increases heating demand in every scenario, but the significance of this amount varies by location, climate, and energy costs. More research is needed for greenhouse operators to make decisions about which type of supplemental lighting is best for their situation. To find these answers, more research on locations and lamp specifications is needed, which was the purpose of this research project.

Supplemental Lighting

One of the most important elements for consistent year-round yields is the amount of usable light the plants receive. Plant growth rate (and thus the amount of yield) is determined by the amount of light the plant receives during the growth cycle. To maintain high productivity, the amount of daily light that plants receive must be consistent and at sufficient levels. This amount of light is called DLI, or Daily Light Integral, and is defined as the "light sum," or the number of photosynthetic photons (across the 400 to 700 nm waveband) received by a plant in one day (Albright & Brechner 2011). The term PAR (Photosynthetically Active Radiation) is used to refer to the instantaneous intensity across this waveband. The DLI number is typically expressed in the units of moles of PAR photons received per m^2 per day. According to Albright and

Brechner (2011), plant growth is proportional to the DLI sum over a plant's entire growth period. Natural light from solar radiation does not produce consistent DLI values and can vary by location due to climate and/or weather patterns. Greenhouse operators use supplemental lighting as a solution for this inconsistency in natural lighting. Using supplemental lighting, plants can achieve their DLI targets for the day even though the sun was not able to provide all the necessary light.

The DLI target is different depending on the type of plant, but for lettuce (a commonly cultivated leafy green) the number is 17 moles of photons per square meter per day. The target DLI is commonly used as a metric to determine the amount of needed supplemental lighting. Whatever light the sun delivers during the day can be compared to the DLI target value for the crop being grown. If the DLI target has not been reached by sundown, then supplemental lighting is required to deliver the rest of the light. This method works for most regions where supplemental lighting is a necessity, with some location exceptions where providing supplemental light in the early morning and/or late evenings when the sun is partially above the global horizon is recommended (Katzin et al, 2020).

It is important that plants receive adequate levels of PAR. Without the proper amount of lighting in the PAR range, plants will not yield as much. Plants can also grow much slower if they do not receive enough PAR. For this reason, greenhouse operations carefully monitor the amount of PAR that plants receive throughout the day to make their supplemental lighting schedules as efficient as possible. There are different variables, however, that contribute to the amount of PAR that plants receive from supplemental lighting. As mentioned before, HPS and LED lamps have different efficiencies in terms of energy and spectral output. In addition to this distinction, lamps have other properties that separate them from HPS lamps that can vary between manufacturers and models. These values are efficacy (or light intensity per unit area) and Photosynthetic Photon Flux Density (PPFD). The efficacy of a lamp can be described as to its ability to convert electrical energy to PAR, and the units are μmol/J. The PPFD of a lamp is a quantifiable measurement of PAR that is delivered to a unit area per second [μmol/m2/s]. It is a similar measurement to DLI. The PAR intensity PPFD) and efficacy can be used to calculate the mounting heights and the number of lamps needed to light a given grow area. The number of lamps directly affects the amount of light that a given growing area will receive. These two properties have different ranges depending on the type of lamp, which will be discussed in the next section.

Although supplemental lighting is necessary in many greenhouse operations, there are concerns regarding their energy consumption. According to Gelder et al, (2020), greenhouses that utilize supplemental lighting for assimilation lighting only yield around 27% more produce while doubling energy costs and tripling the carbon footprint of the operation. To mitigate these costly consequences, research is being done on alternative supplemental lighting products that are more efficient at conversion to PAR. As these products become available, greenhouse operators need to know exactly how much better the new products are and if they are worth the price for their operation.

The topic of supplemental lighting and its role in greenhouse heating was studied by Katzin et al. (2020). This study was published during the time data was being gathered for the current study topic and can serve as a comparison. The Katzin et al. (2020) study looked at the cost impact of switching from HPS lamps to LED lamps. This was done by comparing the heating costs with each type of lighting configuration. They used the efficacies of different LED and HPS lamps to compare energy costs and calculate electricity savings. These energy savings were compared with a model in Greenlight, a MATLAB based greenhouse experimentation program, which was used to calculate heating demands for several different locations around the globe. The results that Katzin et al. (2020) found were that the LED lighting configurations required more heating in every case. The amount was greatly affected by the amount of heating required for a given location (or on a certain day) and the ratio of lighting versus heating costs in different locations due to the local weather. The lighting schedule used kept the lamps on every day between midnight and 6 P.M. The exceptions were when global solar radiation exceeded 400 W/m^2 or if the predicted total global solar radiation for the day was above 10 MJ/m^2/day (~20.8 mol/m^2/day of PAR). This is a much higher threshold than the target DLI of 17 mol/m^2/day that was used to turn off the lights in the current study. The reference settings for the Greenlight model also included CO_2 injection, ventilation and thermal screens for heating and humidity control.

The current study simulated the control of the greenhouse using an energy balance to simulate the greenhouse in several different locations around the United States and the world. The study focused on the energy that is emitted by the supplemental lighting system and how that energy affects the internal temperature of the greenhouse based on outside temperatures. Specifically, this approach is useful for nighttime analysis when lamps are on much of the time. The inclusion of the incoming solar radiation during the day allowed this study to take on a broader scope: A focus on how different lighting arrangements and lamp properties affect the heating requirements.

High-Intensity Discharge Lamps

In climate regions with lower solar radiation (such as at higher latitudes or areas with a higher percentage of cloud cover), optimal yield can only be reached with the use of supplemental lighting. In these cases, electricity becomes the second highest production expense just under labor costs (Shen et al. 2017). The most common type of supplemental lighting currently used in commercial greenhouses are High-Intensity Discharge (HID) lamps. These include High Pressure Sodium (HPS) and metal halide (MH) lamps. Of the HID lamps, HPS lamps are the most widely used, and they emit a red-centered spectrum with a high intensity that is very useful during flowering. They are also commonly used for leafy greens (Shimizu 2016). HPS lights also consume a lot of energy that does not contribute to usable light, which is released as heat. According to Gómez et al. (2013), HPS lights are only approximately 25% efficient in converting electricity to usable light. However, the total energy emitted contributes to the increase in the overall ambient temperature of the greenhouse and to the plants as well.

Since all energy consumed by the lights ultimately becomes thermal heat except the light that escapes out of the greenhouse, this additional heat output can reduce the amount of supplemental heating required particularly on winter nights. According to Brault et al. (1989), this thermal energy released from HPS lamps can provide between 25-41% of the heat required for a greenhouse operation. This extra heat affects the growing conditions and can be a problem in hotter climates. In contrast, this heat may be useful in other conditions and climates such as during nighttime and winter. This study looked at the overall thermal and energy impact if greenhouses were to convert from HPS lamp systems to higher efficiency LED lighting systems.

Fluorescent Lamps

One standard option for lighting is fluorescent lamps, specifically Compact Fluorescent Lights (CFL). They are more energy efficient then HID lamps but are not as widely used (and not for assimilation lighting) because the spectrum of light emitted is not nearly as usable during certain growth periods (Runkle et al. 2012). Most fluorescent lamps, including the CFL, T12, and T8, are commonly used for seedlings and clippings in controlled environments because the light they emit is at a relatively low intensity (low lumen output). This requires fluorescents to be in close proximity to the plants (less than 10”) and makes them less ideal for plants in the growing or budding stages of growth that require more intense light (Fraser, 2008). There is a newer form of fluorescent light called the T5 that outputs 3 times the intensity of other fluorescents per watt input and has been recommended for use in greenhouses. Although these fluorescent lights have their uses and have had improvements, when limiting heat gain and overall energy efficiencies are of concern, LED lights have been the more appealing alternative for many greenhouse operations.

LED Lamps

LED grow lights are more energy efficient than both HID lamps and fluorescents and can be designed to emit light in different wavelengths depending on the light element design. How much more efficient LEDs are is the topic of much research as the industry is highly innovative. Due to these innovations, LED lamps have become much more versatile in conditions where HPS or fluorescent lamps would be more limiting due to their fixed light spectrums. LED fixtures can be installed above the crop canopy (like HPS and fluorescent lighting) or inside the canopy since they release less heat and can be smaller in size. Another main attraction with

LEDs is that they can emit precise wavelengths of light with very little wasted photons or additional waste heat. They are more efficient at delivering photosynthetically active radiation (PAR) to the plants compared to HID lamps because they can be placed in much closer proximity to the plants themselves. LEDs may seem much more appealing because of their energy efficiency in terms of consumption and PAR delivery, however in those conditions where extra thermal energy is needed to heat the greenhouse, conversion from HID lights might not be cost-effective considering initial investment on the LED technology along with these associated losses in total envelope (Katzin et al. 2020). LED lamps are also in a very innovative position in the industry. For years they have been considered to be less cost-effective than HID lamps due to their high capital investment and minimal improvements in efficiency (Runkle & Both, 2012). However, this has been changing year to year and most modern LED lamps have test efficacy values that are higher than their HID equivalents.

Given these lighting options, there are several differences which affect their usefulness for different growing conditions. The differences in heat released by the lighting systems can also impact the overall natural air circulation patterns in CEA facilities. While other researchers have been studying the impact of various wavelengths of light on plant growth, this study was focusing on the energy consumption and the impacts on internal greenhouse operation (such as air circulation). At times, the heat released from grow lights is a benefit, such as during winter nights, but this is not an efficient way to provide heating since the cost of electricity is much higher than natural gas or propane on a per unit of energy basis ($/Btu). Because of this impact, winter nights and climates that are cold or hot for most of the year are of particular interest.

Thermal Stratification

Researchers over the past few decades have been studying thermal stratification in greenhouses (Kittas et al, 2003) (Li & Willits, 2008) (Zhang et al, 2002), but because they assumed that the greenhouse environment was uniform, much of the early research on this topic only focused on the impact of external conditions. Later, researchers recognized the impact of fan-ventilation, but only along the streamlines, or inlet-to-outlet stratification which ignores vertical stratification (Kittas et al., 2003) . Some research was focused on designing mathematical models to represent thermal stratification vertically but ignored the impacts of horizontal stratification along the ventilation streamlines (Zhang et al, 2016) as well as other internal and external factors. In 2008, Li and Willits published research that describes the external and internal factors contributing to thermal stratification in greenhouses. Li and Willits (2008) studied a combination of multiple factors that had been previously shown to impact thermal stratification (the outside temperature data, ventilation rates, and plant canopy locations) in the same study. However, the other element to Li and Willits (2008) research that makes it different from the previous studies (Kittas et al, 2003) (Zhang et al, 2002) is their method of using sensors throughout the greenhouse in both vertical and horizontal positions (measuring along streamlines and the orthogonal direction at the same time). They also used a pyranometer to measure incident solar radiation entering the greenhouse and aspirated box to measure relative humidity and internal greenhouse temperature. Several different situations were measured based on the controllable elements of the systems: Three different canopy sizes along with two different ventilations rates and the use of an evaporative cooling pad on the ventilation inlet. These discrete variables along with the variation in solar radiation and outside weather conditions allowed Li and Willits (2008) to collect a large amount of data for different situations. The results were very sobering; Vertical temperature variation was given as a function of outside solar radiation for high and low ventilation rates with the cooling pad on and off. Trend lines showed a mostly linear relationship, with the lower ventilation rate resulting in higher vertical temperature variation measurements for outside solar radiation values over 200 W/m^2 for both cooling situations. The significance of these results is that Li and Willits (2008) were able to conclude that the thermal stratification is not only greatly influenced by outside solar radiation, but also greatly influenced by horizontal ventilation rate and plant canopy size and height. This brought validity to earlier experiments by other researchers who used one-system focused models, but also demonstrated how thermal stratification is a multi-faceted circumstance and several components should be considered in the energy balance. The work by Li and Willits (2008) is important because they studied a combination of multiple systems that impact the energy balance of a greenhouse. They were able to combine systems that other researchers previously studied individually and experiment with the collective impact of these systems on the internal environment of the greenhouse. This involved the consideration of outside and inside variables but did not quite consider all of them. Recent studies such as by Katzin et al. (2020) suggest that the type of supplemental lighting used in a greenhouse can drastically alter the thermal environment inside the greenhouse. So far, it was not known whether any research regarding supplemental lighting alternatives and their effects on thermal stratification had been conducted.

Virtual Grower

The USDA Agricultural Research Service offers a free software for download called Virtual Grower (Runkle, E. & Frantz J. 2009). This application allows growers to simulate their particular greenhouse system and can be used to predict possible changes in the greenhouse environment that would affect growing conditions. It is a useful tool that accounts for cost changes and the associated crop responses under a range of growing conditions. The application offers many different features including a location finder, multiple space heating options, infiltration/exfiltration, and even supplemental lighting lamps and lighting schedules (for a limited number of crops) to help greenhouse operators customize the program to their specific needs.

Virtual Grower has many useful capabilities; however, it does not calculate any heating contribution from supplemental lighting, nor does it have any LED lighting options whatsoever. Greenhouse operators have been switching to LED lamps for supplemental lighting in several places across the world because of their energy saving benefits. The inclusion of LED lighting in Virtual Grower for energy cost analyses is needed for greenhouse operators to make educated decisions about switching supplemental lighting systems. I will be explain how the type of lamp used for supplemental lighting can considerably affect the magnitude of heating needed to maintain optimal temperature in the greenhouse. Lighting plays an important role in greenhouse heating in a wide range of climates and is therefore a significant factor for production cost calculations. The addition of LED lamps and the conversion efficiencies of lamps would be beneficial to greenhouse operators who wish to use Virtual Grower.

Computational Fluid Dynamics

Zhang et al. (2016) studied negative effects on lettuce crops when air stagnation points within the plant canopy led to calcium deficiency in the inner parts of lettuce plants. This is referred to as "Tip burning." They tested methods of introducing airflow into the canopy from above to create vertical air movement. Using an analytical method called Computational Fluid Dynamics (CFD), they proved that implementing some vertical air flow into the plant canopy can stimulate enough air change to prevent tip burn in lettuce.

Akrami et al. (2019) utilized CFD to find the locations within a typical greenhouse with the highest temperatures and the lowest air movement. These locations typically have higher local air pressures due to low air velocities and poor circulation, and thus have higher relative humidity values. Visuals of the temperature distribution and velocity streamlines along a 2-D plane along the length of the greenhouse were used to identify these locations. Akrami et. al (2019) solved for boundary conditions assuming the greenhouse was located near the equator with a 500 W/m^2 soil heat flux from the subsoil to the floor of the greenhouse. They assumed the sun as a perfect blackbody, solar radiance not being constant, use of the zenith effect, and placed the greenhouse at sea level. The roof vent boundary conditions were set as velocity inlets with air flow acting perpendicular to the vent (normal to the axis of the gable). Steady state flow along with the energy equation, momentum equation, and the k-epsilon turbulence model were implemented along with the Boussinesq equation for simulating natural convection. Air density was set to 1.225 kg/m3, coefficient of thermal expansion was set to 0.0034 -1, and a velocity of 0.81 m/s in the neg-x direction was set as an initial condition. This study decided to test one vent size for the inlet vents, being 0.5 m x 1.0 m. They found that changing the vertical placement of the roof vents did not affect the temperature distribution or velocity profile streamlines inside the greenhouse. They did find, however, for both tested inlet velocity conditions of 0.2 m/s and 1.0 m/s, that the opposite end of inlet flow location was in fact thermally insulated and had poor air velocity and circulation. By adding condenser effects to that far side of the greenhouse opposite the vent inlet, the temperature decreased, and the air velocity increased.

Solar radiation and natural convection are the largest modes of heat transfer in a greenhouse, but Akrami et al (2019) claims that their analysis of airflow and temperature distribution can be analyzed on natural convection alone, disregarding solar radiation. They simulated a real greenhouse, 307 m^3, located at the University of Bologna in Bologna, Italy. The CFD program used was Autodesk CFD 2015 using finite element analysis, which yields algebraic equations for the dependent variables at every node in the mesh. The authors claim that this is the best method for their CFD analysis. The governing equations for fluid dynamics used were the momentum equation, energy equation, and Reynold's Average for the Mixing Length turbulence model. This turbulence model was chosen for its ability to calculate eddy viscosity and is designed for internal gas flows.

The boundary conditions were clearly defined, with meteorological data being used for inlet conditions in the inlet vents, and external sensors used to measure external temperatures for the model. All other initial conditions for the internal environment of the greenhouse were measured using sensors installed in the real greenhouse. Measurements were taken with the vents closed and open to evaluate results.

The Akrami et al. (2019) study described three simulations: one with all vents open, one with side vents and windward vent open but leeward closed, and one with side vents open and windward vent closed but leeward vent open. They concluded that the model with the windward vent open was the most effective at removing heat and reducing temperature while maintaining desired air circulation. This model removed 64% of heat while the others only removed around 50%.

CHAPTER 3

METHODOLOGY

Greenhouse Model

Establishing a “Typical Greenhouse” model was of utmost importance since the greenhouse would need to be simulated under the conditions of different climates. The same greenhouse needed to be used for each location-scenario to properly compare the resulting differences in internal thermal environment in each scenario. Since the results would need to be compared in a per unit-area metric, it made since to use an “average-sized” greenhouse to solve for this value. The University of Georgia and its extensions owns dozens of both large and small-scale agriculture operations all of the state, many of which have greenhouses. On the main campus in Athens, Georgia, the Department of Horticulture operates several greenhouses for research purposes. One of the facilities is on Riverbend Avenue, where there are a few medium-sized, gable style greenhouses that are used for experimental growing. One of these greenhouses served as the basis for the model greenhouse used in this study. The greenhouse typically used for a variety of different trials can be run under different experimental conditions. The greenhouse utilizes both HPS and LED lamps of different types.

Figure 3.1 shows a 3-D rendering of the greenhouse. This is an external view of the greenhouse to show the general design. This is the CAD model used for the Computation Fluid Dynamics portion of this study. It has the same width, length, height, and general setup as the greenhouse on Riverbend Avenue.

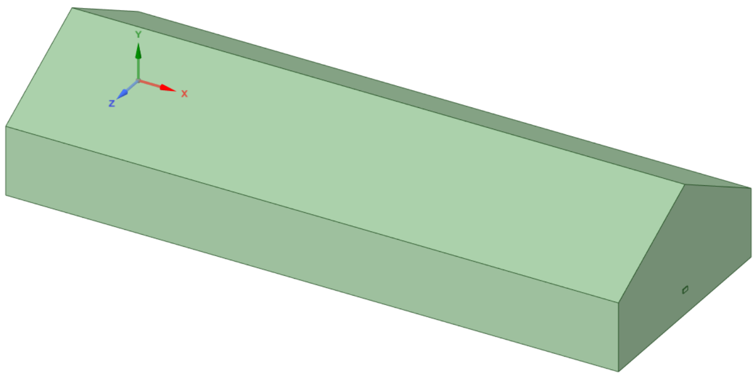


Figure 3.1 – 3-D Rendering of Riverbend Greenhouse that was used as the model greenhouse in this study.

The Riverbend Ave Greenhouse is 80 long and 30 feet wide. The wall height is 9 feet, and the gable height is 8 feet combining to height of 17 feet at the ridge. The ground is solid concrete, and the walls and roof are made from single pane greenhouse glass. The Riverbend Greenhouse is split into three sections where different environments are maintained (different crops, lamps, cooling pads, etc.), however for this study the greenhouse was treated as one environment throughout. The small vent seen on the front face of the greenhouse in Figure 3.1 is where the air inlet is placed for the CFD fluid flow, it is not representative of the actual greenhouse. An outlet of the same size is on the opposite wall. More difference between the two are that unlike the Riverbend Ave Greenhouse, the model greenhouse does not contain an evaporative cooling pad, automated ventilation control, or multiple lamp types at the same time. It was important that the model greenhouse be simple and shell-like so that the same variables could be easily controlled for all locations. The focus of this study was on the lamp types used. Therefore, the aforementioned technologies were not considered so the study could yield results dependent on the lighting types alone.

Parametric Solver for Bulk Internal Temperature

Engineering Equation Solver (EES) is a software program that is used to solve algebraic engineering equations that are generally lengthy or complex. F-Chart Software, the creator and distributor of EES, describes EES as a general equation-solving program that can numerically solve thousands of coupled non-linear algebraic and differential equations (Klein, 2020). By defining variables, and then creating matrices from strings of equations, the program is capable of calculating solutions to engineering problems with any given number of constraints. Because of its robust interface, EES serves as a great tool for the purposes of this study.

EES was used to solve for the magnitude of energy input needed to heat a typical greenhouse depending on a wide range of different outdoor temperature values. The ability to solve parametrically makes EES a great choice because the output table can be used to easily compare different inputs. Part of the process was setting up the EES solver to calculate the Bulk Indoor Air Temperature (T_{Bulk}) of a theoretical, average-sized greenhouse without any supplemental lighting. The first step in designing the EES was to define the variables and equations needed to solve for the greenhouse air temperature. Using the air temperature, an equation defining the energy balance of the system would be written. Using estimated values for the greenhouse boundaries, an estimated bulk internal air temperature was calculated and used as an initial value that was then used in the parametric solver. An EES summary including formatted equations and full output table can be found in Appendix A.

Greenhouse Material Properties

The Riverbend Ave Greenhouse was used for defining the characteristics of the materials that make up the structure of the model greenhouse. For the heat transfer equations to be solved, there are defining material properties that must be known for the materials involved (Figure 3.2).

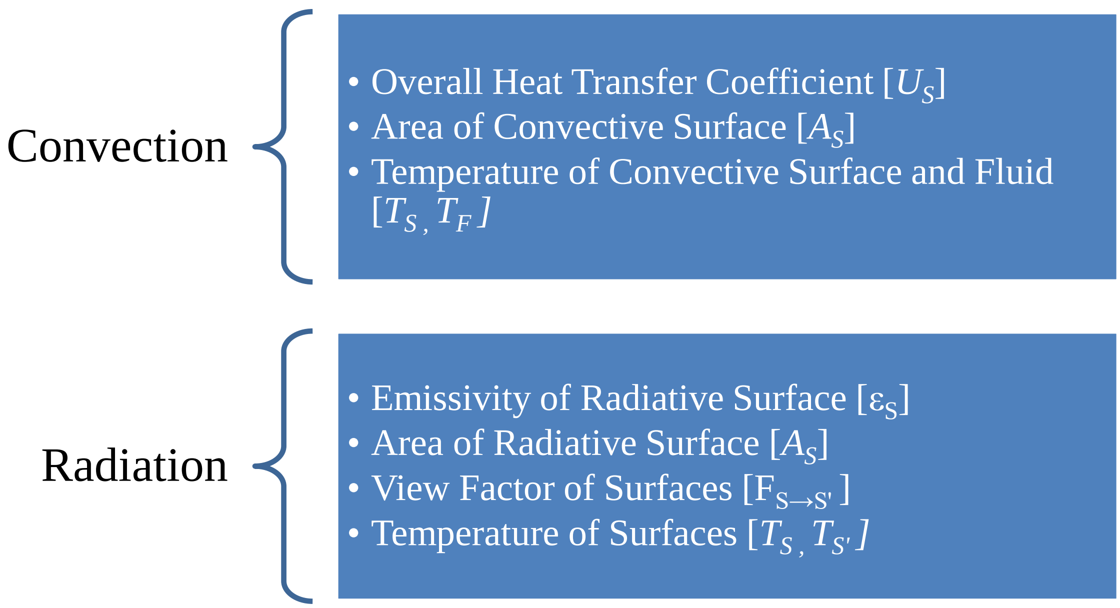


Figure 3.2 – Heat Transfer & Material Properties of the model greenhouse surfaces.

Some of these properties, such as the emissivity of glass, were assumed to be intrinsic to their materials of which they consist. Some values were retrieved from the literature and engineering tables. The other remaining values needed to be calculated measurements conducted at the Riverbend Ave Greenhouse. Equations 3.1 – 3.4 were used to find these unknown properties that were needed for the EES. A combination of view factor equations was used to find the view factors for the wall to roof and for the ground to the roof. This was needed because the angle of the roof was beyond the orthogonal plane. So, for wall to roof view factors, the equation for surfaces sharing an orthogonal edge (Equation 3.1) was used and then inserted into the equation for surfaces sharing an edge at an angle (Equation 3.2). The same method was used for finding the view factors for the ground to the roof using first Equation 3.3 and then Equation 3.2. Equation 3.4 contains the series of equations needed to find the convective heat transfer coefficient for a surface. Once several physical properties about the surface material and the fluid are known, the Nusselt Number can be solved from Grashoff's Number (ratio of buoyancy forces to viscous forces), the Prandtl Number (an intrinsic value to the material), and the Rayleigh Number (describes the fluid flow along a surface). The Nusselt Number can then be used to find the heat transfer coefficient if the length of the material and the thermal conductivity $[K]$ are known.

Equation 3.1 – View Factors – Surfaces sharing Orthogonal Edge (Cengel & Ghajar, 2014)

$$F_{S \to S'} = \left\{ 1 + \frac{W_{S'}}{W_S} - \left[1 + \left(\frac{W_{S'}}{W_S} \right)^2 \right]^{1/2} \right\}$$

$$W_S = Width\ of\ Surface\ S \quad \& \quad W_{S'} = Width\ of\ Surface\ S'$$

Equation 3.2– View Factors – Surfaces Sharing Edge at Angle (Cengel & Ghajar, 2014)

$$F_{S \to S'} = 1 - \sin \frac{1}{2} \alpha$$

$$\alpha = Angle\ at\ shared\ edge$$

Equation 3.3 – View Factors – Aligned Parallel Rectangles (Cengel & Ghajar, 2014)

$$F_{S\rightarrow S'} = \frac{2}{\pi XY}\left\{\ln\left[\frac{(1+X)^2(1+Y)^2}{1+ X^2+Y^2}\right]^{\frac{1}{2}}\right.$$

$$+ X(1+ Y^2)^{\frac{1}{2}}\tan^{-1}\left[\frac{X}{(1+ Y^2)^{\frac{1}{2}}}\right]$$

$$\left.+ Y(1+ X^2)^{\frac{1}{2}}\tan^{-1}\left[\frac{Y}{(1+ X^2)^{\frac{1}{2}}}\right] - X\tan^{-1}(X) - Y\tan^{-1}(Y)\right\}$$

$$Where\ X = \frac{Width\ of\ Radiative\ Surface}{Distance\ between\ Surfaces} \quad \& \quad Y = \frac{Length\ of\ Radiative\ Surface}{Distance\ between\ Surfaces}$$

Equations 3.4 – Heat Transfer Coefficient (Cengel & Ghajar, 2014)

$$Grashoff's\ Number: \quad Gr = \frac{gB(T_S - T_\infty)L^3}{\nu^2} \qquad Prandtl\ Number: \quad \mathrm{Pr} = \frac{\nu}{\alpha}$$

$$Rayleigh\ Number: \quad Ra = GrPr \qquad Nusselt\ Number: \quad Nu = \left\{0.825 + \frac{0.387Ra^{1/6}}{\left[1+\left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}}\right\}$$

$$Heat\ Transfer\ Coefficient: \quad h = \frac{Nu\cdot K}{L}$$

$$g = Graviational\ Acceleration \quad B = Volume\ Expansivity \quad T_S$$

$$= Temperature\ of\ Convective\ Surface$$

$$T_\infty = Air\ Temperature \quad \nu = Momentum\ Diffusivity \quad \alpha = Thermal\ Diffusivity$$

$$L = length\ of\ Convective\ Surface \quad K = Thermal\ Conductivity$$

The temperature values of the walls, roof, and ground were first given estimates to initialize the solver. These input values were removed and replaced with an energy balance so the solver could calculate the steady state temperature of these surfaces as well. Values for the greenhouse glass material were obtained from Albright (1990) and Garzoli & Blackwell (1981). The view factors and the heat transfer coefficient for the greenhouse floor (ground) were calculated using Equations 3.4. The emissivity of glass is equal to the absorptivity of incident solar radiation. Other emissivity values were found in engineering tables. The areas of each surface were found using the dimensions of the Riverbend Ave Greenhouse as a reference for the creation of the model greenhouse. The full list of physical properties used in the EES model can be found in Figure 3.3 below as well as in the EES Summary in Appendix A.

Areas

- Gable Walls 1 & 2: 25.1 m^2
- Side Walls 3 & 4: 66.9 m^2
- Ground: 223 m^2
- Roof: 252.7 m^2
- Growing Area: 110 m^2

Heat Transfer Coefficients

- Walls & Roof: 7.2 $\frac{W}{m^2K}$
- Ground: 9.0 $\frac{W}{m^2K}$
- Growing Area: 20.9 $\frac{W}{m^2K}$

Emissivities

- Walls & Roof: 0.98
- Plants: 0.98
- Ground: 0.95

View Factors

- Walls 1&2 to Ground: .128
- Walls 3&4 to Ground: 0.106
- Walls to Sky: 0.883
- Walls to Roof: 0.1
- Ground to Roof: 0.6
- Plants to Roof: 0.6
- Plants to Wall: 0.03

Figure 3.3 – Greenhouse Material Properties for EES Solver

Energy Balance

The purpose of designing the EES was to find the required heating energy to meet the greenhouse setpoint temperature based on a wide range of outdoor temperature values. To obtain this information, it was necessary to first solve for the bulk indoor air temperature of the greenhouse for each input outdoor temperature value across a wide range of values. The range of values needed to be representative of all seasonal temperatures for locations all over the world. The chosen range was 244K (-29°C) to 320K (47°C). The Bulk Indoor Air temperatures were found by the EES solver for each of 50 outdoor temperature values within this range. EES worked through the comprehensive set of heat transfer and energy balance equations that define the model greenhouse. Each surface within the greenhouse system has a set of equations that defines the heat transfer between itself and its surroundings and relating to the bulk indoor temperature value. The heat transfer relationships between these surfaces are summarized in Figure 3.4.

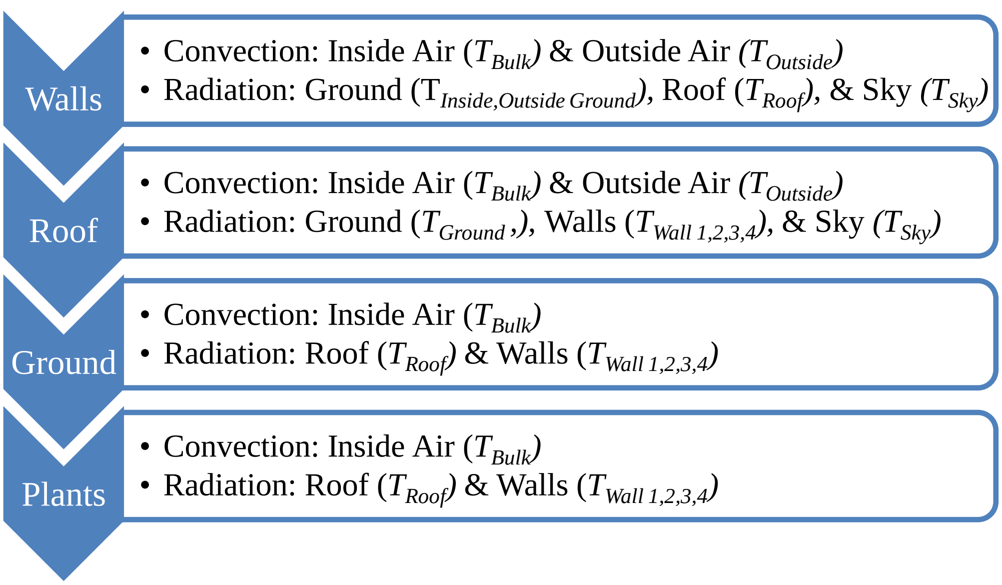


Figure 3.4– Summary of Energy Equations

Equation 3.5 – Overall Energy Balance

$$\sum \dot{Q}_{Wall\ 1,2,3,4} + \sum \dot{Q}_{Roof} + \sum \dot{Q}_{Ground} + \sum \dot{Q}_{Plants} = 0$$

The sum of equations must be equal to zero since there is no energy input into this system. Form here, the solver will only be able to calculate heat transfer between the surfaces based on temperature differences and the defined specifications for each material surface.
To initialize the solver, initial conditions were used as estimates until each interacting body and surface was defined by energy equations explaining the convective and radiative heat transfer between itself and its surroundings. These equations define the energy transfer between the outside air and the internal environment of the greenhouse. The heat transfer in and out of the greenhouse is calculated based on temperature differences between all interacting surfaces and bodies. From this system of equations, the parametric solver was able to input dozens of outdoor temperatures and calculate what the internal bulk temperature of the greenhouse would be without any external energy input. Simulating nighttime energy balance was the goal, so no energy input could be added to ensure a steady state temperature was found. This way, each arrangement of lamps discussed could be simulated with the same baseline conditions.

The results of the parametric solver are summarized below in Table 3.1. Each iteration out of the total of 50 were averaged and presented in the table. For the full table of all 50 iterations of the parametric solver, see Appendix A.

Table 3.1 – Summarized Results of Engineering Equation Solver (EES)

Outdoor Dry Bulb Temperature [K]	Temperature Difference [K]	Bulk Indoor Air Temperature [K]	Heating requirements (therms)
251	49.5	244.48	0.507
266.5	29.7	264.32	0.304
282	9.28	284.72	0.095
297.5	-11.7	305.74	0
313	-33.4	327.42	0

The temperature differences in the second column of Table 3.1 refer to the temperature setpoint, which was 294 K (21°C). Lettuce crops are a common crop used for greenhouse research purposes and a common crop grown in commercial greenhouses (Zhang et al, 2016). The solver used this temperature difference to calculate the heating energy required to meet this temperature setpoint. There was a 100% efficiency assumed for this heating value because it refers to the total amount of energy needed for heating, and not the heating load. This was an important distinction because the energy can come from any source, especially with the primary focus of this study on the heat produced by grow lamps. In the next section where the supplemental lighting arrangements are discussed, the heating contribution from supplemental lighting will be calculated and compared to these deficit heating values. The remaining required heating after lighting is the heating load left to the space heating system.

What is notable about the EES output table is that some of the Bulk Indoor Air Temperatures are lower than the Outdoor Air Temperature. This occurs for the coldest range of temperatures only, and the Bulk Indoor Air Temperature becomes higher than the Outdoor Air Temperature when the Outdoor Air Temperature reaches around 275 K (2°C), which is around the freezing temperature of water. This occurs because, at these low outdoor temperatures, the heat transfer leaving the greenhouse is higher than the heat transfer directed towards the internal greenhouse temperature.

Lighting Arrangements

Grow lamp manufacturers advertise a wide range of efficacy and PPFD values for their lamp products. Having this data makes it easier to design a lighting system, but the problem is that we often do not know how accurate this data is. This can make it difficult to discern the proper lamp specifications when designing lighting arrangements. As mentioned before, the PPFD value is directly related to the height of the lamp and therefore the number of required lamps. The efficacy affects the number of lamps required as well, and the relationship between the two is inversely proportional (Equations 3.6). For the purposes of this study, each of the ten locations had simulated scenarios using fifteen different lighting arrangements for each lamp type. There were three different PPFD values and five different efficacy values for each HPS and LED simulation. The PPFD values were kept the same between the lamps (100 $\mu mol/m^2/s$, 200 $\mu mol/m^2/s$, and 300 $\mu mol/m^2/s$) while the efficacy values and scales varied somewhat between lamp types. Since the efficacy is related to the electrical conversion efficiency of the lamp, the LED lamps were assumed to have on a higher efficacy range than the HPS lamps. Using a simple formula (Equations 3.6), the number of lamps for each arrangement was determined using these specifications. Tables 3.2 and 3.3 list the HPS and LED lamp characteristics that were simulated. The variable that is not included is the height of the lamp. Since the mounting height is directly proportional to PPFD, the number of lamps was used as the dependent variable, and the height was kept constant. After the number of lamps was determined, the DLI contributions were calculated for each of the various lighting arrangements (Equations 3.6).

Equations 3.6 - For Lighting Arrangement Contributions

$$N_L = \frac{A_P \times PPFD}{\eta \times P} \qquad DLI = \frac{N_L \times P \times T \times \eta}{A_P}$$

$$N_L = Number\ of\ Lamps \qquad A_P = Plant\ Area\ [m^2]$$

$$PPFD = \ Photosynthetic\ Photon\ Flux\ Density\ \left[\frac{mol}{m^2 s}\right]$$

$$\eta = Efficacy \quad P = Power\ [W] \quad T = Time\ [s]$$

HPS lamps, like other HID lamps, convert approximately 30% of the input electricity in useful light. However, this does not mean that they do not adequately deliver PAR to plants. While they release most of their energy as radiant heat below the usable spectrum of light (PAR), they can produce a lot of photons in comparison to LED lamps. They also have higher rated wattages. The HID lamps used for simulation in this study were 1000W HPS lamps with 75W ballasts. Specifications and sizes were based on averages from different products on the market. The efficacy values used for simulation scenarios were 1.5, 1.75, 2.0, 2.25, and 2.5 µmol/J. Table 3.2 summarizes characteristics for each HPS lighting configuration simulated.

Table 3.2 – Simulated High-Pressure Sodium (HPS) Characteristics

Efficacy (mol/J)	Photosynthetic Photon Flux Density (mol/m^{2}s)	Wattage	Plant Area (m^2)	Number of Lamps	Heat Energy from Lamps [W]	Daily Lighting Integral Contribution (mol/m^{2}h)
1.50E-06	1.00E-04	1000	110	8	6580	0.39
1.75E-06	1.00E-04	1000	110	7	5758	0.40
2.00E-06	1.00E-04	1000	110	6	4935	0.39
2.25E-06	1.00E-04	1000	110	5	4113	0.37
2.50E-06	1.00E-04	1000	110	5	4113	0.41
1.50E-06	2.00E-04	1000	110	15	12338	0.74
1.75E-06	2.00E-04	1000	110	13	10693	0.74
2.00E-06	2.00E-04	1000	110	11	9048	0.72
2.25E-06	2.00E-04	1000	110	10	8225	0.74
2.50E-06	2.00E-04	1000	110	9	7403	0.74
1.50E-06	3.00E-04	1000	110	22	18095	1.08
1.75E-06	3.00E-04	1000	110	19	15628	1.09
2.00E-06	3.00E-04	1000	110	17	13983	1.11
2.25E-06	3.00E-04	1000	110	15	12338	1.10
2.50E-06	3.00E-04	1000	110	14	11515	1.15

LED lamps are the newer alternative to HID lamps. As cited in the literature, they are more efficient than HPS lamps at converting electrical energy to usable light. Efficacy values for LED lamps are sometimes overstated by manufacturers. However, most models of LED lamps still have much higher efficacy values than HPS lamps. As LED technology continues to improve, the efficacies continue to rise with newer models. The LED lamps used for simulation in this study drew 630W and the specifications chosen are based on averages from different products on the market. The efficacy values used for simulation scenarios were 2.0, 2.375, 2.75, 3.125, and 3.5 µmol/J. Table 3.3 summarizes the characteristics for each of the LED lighting configurations simulated.

Table 3.3 – Simulated Light-Emitting Diode (LED) Characteristics

Efficacy (μmol/J)	Photosynthetic Photon Flux Density (μmol/m^2s)	Wattage	Plant Area (m^2)	Number of Lamps	Heat Energy from Lamps [W]	Daily Lighting Integral Contribution (mol/m^2h)
2.00E-06	1.00E-04	630	110	9	2835	0.37
2.38E-06	1.00E-04	630	110	8	2520	0.39
2.75E-06	1.00E-04	630	110	7	2205	0.40
3.13E-06	1.00E-04	630	110	6	1890	0.39
3.50E-06	1.00E-04	630	110	5	1575	0.36
2.00E-06	2.00E-04	630	110	18	5670	0.74
2.38E-06	2.00E-04	630	110	15	4725	0.73
2.75E-06	2.00E-04	630	110	13	4095	0.74
3.13E-06	2.00E-04	630	110	12	3780	0.77
3.50E-06	2.00E-04	630	110	10	3150	0.72
2.00E-06	3.00E-04	630	110	27	8505	1.11
2.38E-06	3.00E-04	630	110	23	7245	1.13
2.75E-06	3.00E-04	630	110	20	6300	1.13
3.13E-06	3.00E-04	630	110	17	5355	1.10
3.50E-06	3.00E-04	630	110	15	4725	1.08

MATLAB Solver

MATLAB is a programming and numeric computation application that is often used by engineers and programmers for solving complex data problems. It can be used for large scale data analysis alike to R and Python, but the user interface makes it much simpler to use out-of-the-box. Greenlight is a software program written within the MATLAB environment that was utilized by the Katzin et. al (2020) study. Greenlight is specifically designed to be used by greenhouse operators and researchers to simulate growing environments with full customization. Because it is coded in MATLAB, the program is fully transparent, allowing the user to alter and manipulate the code as they please. This opens MATLAB's capabilities as a comprehensive solver for greenhouse applications. Although Greenlight is specifically for greenhouses, scope of this study required a full energy balance which was computed in EES. The MATLAB applications for this study were purely numerical, so a unique solver was designed.

The goal of the MATLAB solver was to obtain the total amount of annual heating required to maintain the 294K temperature setpoint for all ten locations. This was most useful because the supplemental lighting contribution to the heating load could be compared to this number. The annual heating requirements will vary with weather conditions, but so will the amount of required lighting. Therefore, these are both important values that were solved for independently. After all the data was gathered, the supplemental lighting contributions to heating would be subtracted from the nightly annual heating requirements, leaving the amount of heating that would be left to the heating system.

Greenhouse operations can vary wildly depending on location. Katzin et al. (2020) demonstrated that weather data from different locations is necessary to draw general conclusions about the impact of supplemental lighting alternatives. For this study, ten different locations were chosen including six US cities and four cities in other countries. Factors that can lead to varying results between locations include latitude (global horizontal position), incident radiation, and regional or local weather conditions. Table 3.4 shows the ten different locations and some key characteristics.

Table 3.4 – Locations and some key information

Location	Latitude	Average Lighting Hours from Typical Meteorological Year data
Athens, GA USA	33.95°	665
Casper, WY USA	42.85°	916
Columbus, OH USA	39.96°	1422
Montpelier, VT USA	44.26°	1819
Phoenix, AZ USA	33.45°	198
Redmond, OR, USA	44.27°	1259
Arcen, the Netherlands	51.48°	1914
Beijing, China	39.90°	451
Grand Central, South Africa	25.99°	13
Sydney, Australia	33.87°	458

To calculate the annual nighttime heating requirements for each location, MATLAB needed to open and work with the EES Output Table and the Typical Meteorological Year (TMY) data for each location. For each hour of the year when the Global Horizontal Irradiance was zero (after sundown and before sunrise), the outdoor dry bulb temperature was taken and compared to the temperature setpoint. If the outdoor temperature was below 294K, then MATLAB would interpolate that temperature with the EES output to calculate the associated required heating capacity the greenhouse would need to maintain the temperature setpoint. This value was then converted to a running total, and the end result was an annual sum of required heating capacity.

No supplemental lighting was considered in this calculation. The result was the total amount of heating needed to raise the bulk internal temperature of the greenhouse to the temperature setpoint. Next, any heating contribution to the greenhouse would be subtracted from this number, leaving the remainder as the heating capacity that needed to be delivered by the greenhouse heating system. The full MATLAB code is included in Appendix B.

Lighting Schedules

The TMY data from each of the ten locations was formatted as a spreadsheet and used to calculate the number of hours of supplemental lighting that was required to meet the DLI requirement after sundown. No supplemental lighting was used during daytime hours. Nighttime hours were identified as hours where the Global Horizontal Irradiance was equal to zero. Using the target DLI of 17 mol/m^2 of PAR, each location was tested with thirty different lighting arrangements for nightly supplemental lighting. See Tables 3.2 and 3.3 for the lighting configurations including number of lamps and DLI contribution per hour. The number of lighting hours required for each location per lighting simulation can be found in Appendix C.

The TMY spreadsheet for each location was altered and saved as a copy for each of the 30 supplemental lighting configurations. Each of these 300 spreadsheets had three columns inserted that were used for calculating important information. The first added column summed the amount of PAR received each day from sunlight. These DLI – sunlight values were calculated from the Global Horizontal Irradiance (GHI) values at each hour using Equation 3.7 and the total was left on the cell corresponding with the last hour of the day. The second added column considered the supplemental lighting simulation contribution to the DLI. If the PAR received from the sun by sundown was less than 17 mol/m^2d, then the second column would take the DLI received by the sun from the daytime and conduct a running total, adding the corresponding lighting simulation DLI contribution for each hour. When the target DLI of 17 mol/m^2d was reached, the running total stopped (lamps were turned off). The third added column was simply binary and signified that the lamps were either on with a “1” or off with a “0”. This was determined from the occupation of cells in the second column.

Equation 3.7 – Global Horizontal Irradiance(GHI) to PAR Conversion

$$PAR\ \left[\frac{mol}{m^2}\right] = 5.818 \times 10^{-3} GHI\ \left[\frac{W}{m^2}\right]$$

Using this binary third column, the total amount of hours that the lamps were on during the TMY was summed. Also calculated from the TMY spreadsheets was the annual accumulated PAR contributed by the sun (Sun PAR). The total Sun PAR for each location was considered as a proxy for a linear regression model. This was tested against two other proxies: The latitude and annual Heating Degree Days (HDD) of each location.

Thermal Stratification and CFD

The focus of this study was mostly on the energy balance and strict constraints based on set physical properties and parameters. The only variables were the different locations that were analyzed, and the range of lighting specifications used for the different lighting simulations. This method of analysis does not include the qualitative representation of the data. Luckily, there are engineering tools that allow us to compare data visually as well as mathematically under a set of defined constraints. Computational Fluid Dynamics has been used by several different researchers for purposes involving greenhouses as mentioned in the literature. None of these studies focus on the use of supplemental lighting, so CFD does serve a purpose for this study. As discussed previously, thermal stratification is an issue of concern that has not been heavily researched with regard to greenhouse environments. This is due in part to adequate ventilation systems that are able to maintain sufficient air exchanges to move excess heat out the greenhouse. Since a conversion from HPS to LED lamps changes the heat generation in a greenhouse, a closer look is needed at the impact this as on temperature management. The program used for this study was ANSYS® Fluent® (ANSYS, Inc., Canonsburg, PA, USA) operated on a Student License.

For this study, it was necessary to look at a comparison between LED and HPS lamp configurations. Cross-sectional views of the steady state results of the CFD analysis would yield visual results for comparing air temperature patterns between the two lighting systems. The same arrangement was used for both of the lighting scenarios, with 14 lamps of the same size (total top-down area of 2.5 ft^2) and benchtops to represent tables with crops. Figure 3.5 depicts the transparent view of the 3-D rendering of the Riverbend Ave Greenhouse showing benches an lamps. Figures 3.6 and 3.7 give the dimensions of the Typical Greenhouse Model. The model was designed using the SpaceClaim application that is available with the FLUENT license. The meshing was performed via FLUENT Mesher. The 3D rendering of the mesh is shown in Figure 3.8.

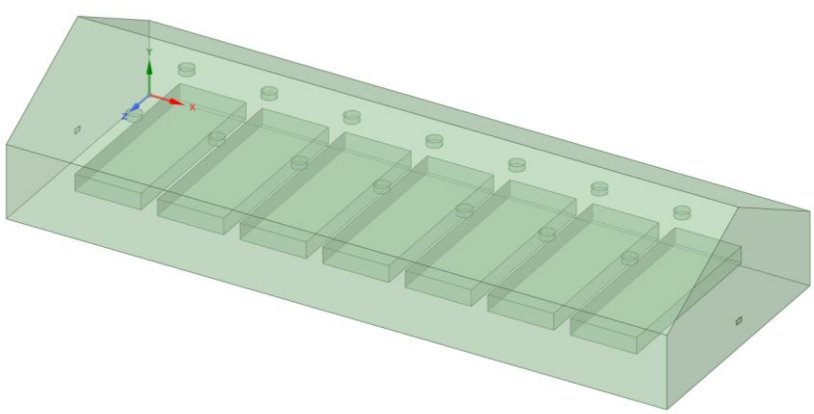


Figure 3.5 – 3-D Rendering of model greenhouse (Transparent).

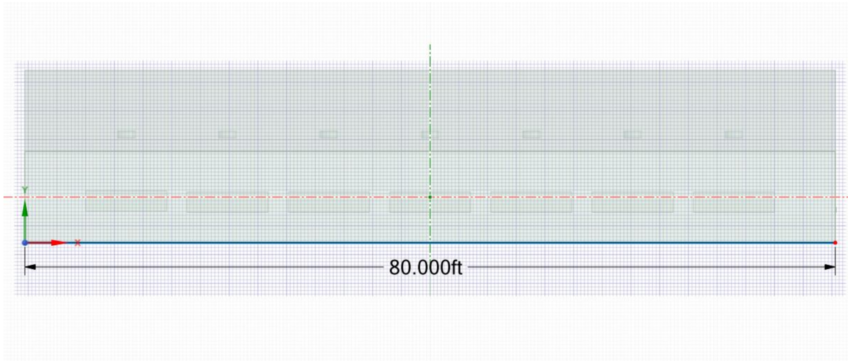


Figure 3.6 – East View of the model greenhouse.

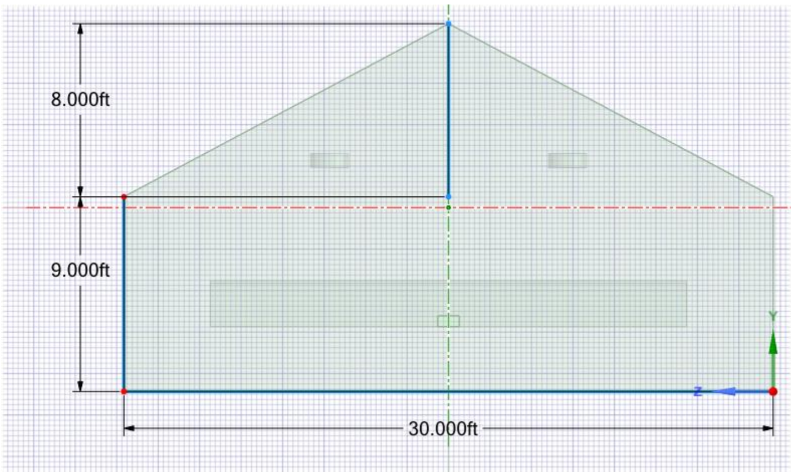


Figure 3.7 – North View of the model greenhouse.

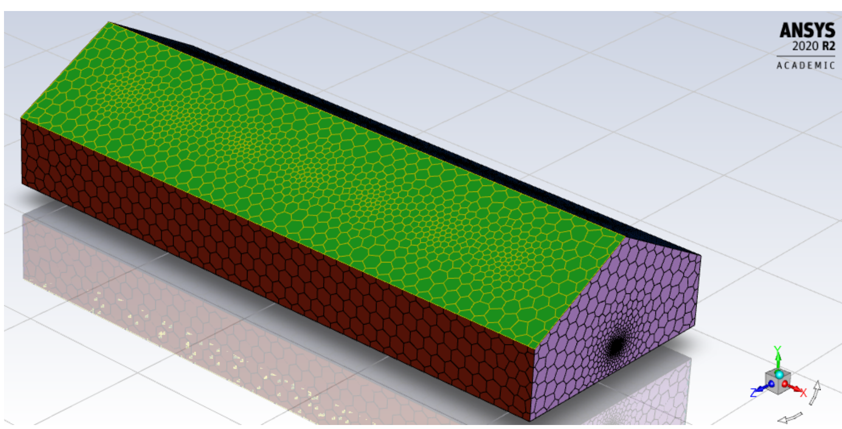


Figure 3.8 – Mesh Rendering of the model greenhouse.

The specifications implemented in the CFD solver were intentionally left simple and similar to the specifications considered in the EES solver, but with no outside heat transfer. FLUENT is capable of performing most of the necessary heat transfer calculations from material values, physics properties, and boundary conditions specified as initial conditions. The Energy Equation model was turned on and the laminar model was turned on for viscous (fluid) settings. Surface-to-surface radiation modeling without solar ray tracing was implemented to ensure that the heat inside the greenhouse was provided by the lamps only. The materials were left to default specifications with the fluid being air and the solid being aluminum. Since solar radiation into the greenhouse was absent, the transmissivity of the glass was not necessary to consider. Also, the majority of the surface area of the lamp (facing downwards towards plant canopy) is a reflective metal surface. The specifications for all boundary conditions were kept the same for both lighting scenarios, with the only difference being the lamp wattage. The LED lamps were 630 W units and the HPS lamps were 1000 W units with 175 W ballasts. The respective heat fluxes used at the boundary condition for the lamp surfaces were 2716 W/m^2 for the LED lamps and 4300 W/m^2 for the HPS lamps. The boundary conditions for structural objects were non-moving walls with no slip conditions. Thermal conditions for all boundary conditions not contributing to energy input were set to system coupling. A minimum input air velocity was necessary for Fluent to properly calculate a steady state, so small inlet and outlet vents (1ft x 0.5 ft) were placed at either end of the greenhouse. The inlet velocity was set to $1x10^{-4}$ m/s to minimize the effect of forced convection on the steady state solution.

CHAPTER 4

FINDINGS

Lighting Contribution to Heating

Using the MATLAB solver with no supplemental lighting and the same setpoint of 294 K (21°C), the annual amount of nightly heating required for each location is shown in Table 4.1. For the lighting contribution to heating, HPS lamps were considered to convert 70% of their energy input to radiant heating and LED lamps were considered to convert 50% of the energy input to convective heating. The number of annual lighting hours for each simulation (Tables 3.2 and 3.3**)** were used to calculate the bulk heating contributed to the greenhouse for each location and lighting configuration. The resulting heat contributions from supplemental lightings are shown in Table 4.2. Table 4.3 shows the remaining amount of heating required after lighting for each simulation.

Table 4.1 – Required Annual Nightly Heating by Location (kWh/m^2y).

Athens, GA	Casper, WY	Columbus, OH	Montpelier, VT	Phoenix, AZ	Redmond, OR	Arcen, NL	Beijing, CN	Grand Central, SA	Sydney, AU
60.36	173.59	119.98	171.91	23.08	158.59	113.39	122.39	36.52	17.31

Table 4.2 – Annual heat gain from supplemental lighting by location (kWh/m^{2}y).

Athens, GA	Casper, WY	Columbus, OH	Montpelier, VT	Phoenix, AZ	Redmond, OR	Arcen, NL	Beijing, CN	Grand Central, SA	Sydney, AU
50.55	75.35	106.49	134.34	15.72	96.81	134.51	40.52	1.14	40.87
43.87	65.20	92.50	117.23	13.70	84.29	117.44	34.51	0.99	35.09
37.92	56.52	79.87	100.75	11.79	72.61	100.89	30.39	0.85	30.66
31.78	48.07	67.26	84.71	10.01	61.14	84.48	26.44	0.75	26.22
31.19	46.20	65.73	83.25	9.71	59.79	83.74	24.39	0.67	0.67
74.51	97.26	161.12	205.72	21.51	139.83	224.43	44.15	1.23	49.30
64.58	84.29	139.64	178.29	18.64	121.19	194.50	38.26	1.07	42.73
55.71	73.21	119.47	153.82	15.94	104.60	165.89	33.11	0.99	37.14
49.67	64.84	107.41	137.14	14.34	93.22	149.62	29.43	0.82	32.87
44.71	58.35	96.67	123.43	12.91	83.90	134.66	26.49	0.74	29.58
80.69	102.71	175.34	229.90	23.01	152.17	249.29	46.34	1.48	52.26
69.12	87.71	150.01	196.71	19.73	129.86	213.88	39.74	1.28	44.71
61.46	77.33	131.81	172.70	17.40	114.16	187.94	35.17	1.14	39.24
54.57	68.80	117.42	153.61	15.46	101.96	167.51	31.37	1.01	34.96
48.84	61.80	105.73	137.20	13.91	90.88	149.75	28.13	0.94	31.27
21.91	33.14	46.37	58.39	6.90	42.15	58.24	18.23	0.51	18.07
19.36	28.86	40.78	51.45	6.02	37.08	51.52	15.52	0.43	15.65
16.80	24.97	35.42	44.90	5.25	32.28	44.98	13.22	0.38	13.44
14.52	21.64	30.59	38.59	4.51	27.81	38.64	11.64	0.33	11.74
12.22	18.57	25.83	32.63	3.88	23.49	32.40	10.27	0.30	10.18
34.24	44.70	74.05	94.54	9.89	64.26	103.14	20.29	0.57	22.66
28.75	37.63	62.14	79.69	8.24	54.02	86.21	17.04	0.47	19.14
24.73	32.28	53.48	68.28	7.14	46.41	74.49	14.65	0.41	16.36
22.31	28.90	47.99	61.79	6.35	42.05	67.90	13.04	0.38	14.56
19.40	25.49	41.60	53.55	5.55	36.42	57.76	11.53	0.34	12.93
37.38	47.04	80.17	105.05	10.58	69.44	114.31	21.40	0.70	23.87
31.25	39.61	67.64	88.04	8.82	58.30	95.87	18.03	0.59	20.07
27.18	34.44	58.82	76.55	7.67	50.69	83.36	15.68	0.51	17.45
23.68	29.86	50.97	66.68	6.71	44.26	72.71	13.62	0.44	15.17
21.07	26.82	45.79	60.03	6.01	39.74	65.10	12.10	0.39	13.65

Table 4.3 – Annual heat requirement after supplemental lighting contribution by Location (kWh/m^2y).

Athens, GA	Casper, WY	Columbus, OH	Montpelier, VT	Phoenix, AZ	Redmond, OR	Arcen, NL	Beijing, CN	Grand Central, SA	Sydney, AU
9.80	98.23	13.49	37.58	7.36	61.78	-74.15	133.07	118.85	131.04
16.49	108.39	27.49	54.68	9.38	74.30	-57.08	139.08	118.99	136.83
22.44	117.07	40.12	71.16	11.29	85.98	-40.53	143.20	119.13	141.26
28.58	125.52	52.72	87.21	13.07	97.45	-24.12	147.15	119.24	145.69
29.17	127.39	54.25	88.66	13.37	98.79	-23.38	149.20	119.31	171.24
-14.15	76.33	-41.14	-33.80	1.57	18.75	-164.07	129.44	118.75	122.61
-4.22	89.30	-19.66	-6.38	4.44	37.40	-134.14	135.33	118.91	129.18
4.65	100.38	0.51	18.10	7.14	53.99	-105.53	140.47	119.00	134.77
10.69	108.75	12.57	34.77	8.74	65.37	-89.26	144.16	119.16	139.04
15.65	115.23	23.31	48.48	10.17	74.69	-74.30	147.10	119.24	142.33
-20.33	70.88	-55.36	-57.99	0.07	6.41	-188.93	127.25	118.50	119.65
-8.76	85.88	-30.03	-24.80	3.35	28.73	-153.52	133.85	118.71	127.21
-1.10	96.25	-11.83	-0.79	5.68	44.43	-127.58	138.41	118.84	132.67
5.79	104.79	2.56	18.30	7.62	56.63	-107.15	142.22	118.97	136.95
11.52	111.78	14.26	34.71	9.17	67.71	-89.39	145.46	119.04	140.64
38.45	140.45	73.61	113.52	16.18	116.44	2.12	155.36	119.47	153.84
41.00	144.73	79.20	120.46	17.06	121.51	8.84	158.07	119.55	156.26
43.56	148.62	84.56	127.02	17.83	126.31	15.38	160.37	119.60	158.47
45.84	151.94	89.40	133.33	18.57	130.78	21.72	161.95	119.66	160.17
48.14	155.02	94.15	139.28	19.20	135.10	27.96	163.32	119.68	161.73
26.12	128.89	45.94	77.37	13.19	94.32	-42.78	153.30	119.42	149.25
31.61	135.96	57.85	92.23	14.84	104.56	-25.85	156.55	119.51	152.77
35.63	141.31	66.50	103.63	15.94	112.17	-14.13	158.94	119.57	155.55
38.05	144.68	71.99	110.12	16.73	116.53	-7.54	160.54	119.60	157.36
40.96	148.10	78.39	118.36	17.53	122.17	2.60	162.06	119.64	158.98
22.98	126.55	39.81	66.87	12.50	89.15	-53.96	152.19	119.29	148.04
29.11	133.98	52.34	83.88	14.26	100.29	-35.51	155.56	119.39	151.84
33.18	139.14	61.17	95.36	15.41	107.90	-23.00	157.91	119.47	154.46
36.68	143.73	69.02	105.24	16.37	114.33	-12.35	159.97	119.54	156.74
39.29	146.77	74.20	111.88	17.07	118.85	-4.74	161.49	119.60	158.27

The resulting annual nightly heating load after lighting varies widely by location and lighting configuration. Some of the heating load values are negative which indicates that the heat energy from the lighting delivered more than enough heat to the greenhouse to reach the target temperature setpoint of 21°C at night. This occurs in the locations that required the most supplemental lighting (see Table 3.4 for average annual lighting hours) and for the configurations with the most number of lamps.

Lighting Type Comparisons

Averaging the results from the different configurations was necessary to directly compare the HPS and LED simulations. Each of the 15 configurations for each lamp type was averaged so that the heating contribution could be compared by location. The Average Lighting Contribution to the heating load is measured in kWh/m^2 and the Average Percentage of Contribution to the heating load is the Average Lighting Contribution to Heat Gain given as a percentage of the entire required heating load for each location. These values were then used as a reference to calculate the LED Penalty, which is given in kWh/m^2. The LED penalty value is the magnitude of heating "lost" by switching from HPS lamps to LED lamps. The "lost" heat would need to be made up for by the greenhouse heating system and is an added cost of converting to LED lamps from HPS lamps. The value is given for each location as well as the LED penalty as a percentage of the total heating load. The data is shown in Tables 4.4 and 4.5, respectively.

Table 4.4 – Average Lighting Contribution to heating load by Location and lamp type (High-Pressure Sodium and Light-Emitting Diode).

	Average Lighting Contribution to Heat Gain by Lamp Type (kWh/m²y)									
	Athens, GA	**Casper, WY**	**Columbus, OH**	**Montpelier, VT**	**Phoenix, AZ**	**Redmond, OR**	**Arcen, NL**	**Beijing, CN**	**Grand Central, SA**	**Sydney, AU**
Avg. HPS	53.28	71.18	114.43	147.25	15.58	100.43	157.24	33.90	1.01	35.17
Avg. LED	23.65	31.60	50.78	65.34	6.90	44.56	69.77	15.08	0.45	16.33
	Average Contribution to Total Heat Gain by Lamp Type (%)									
	Athens, GA	**Casper, WY**	**Columbus, OH**	**Montpelier, VT**	**Phoenix, AZ**	**Redmond, OR**	**Arcen, NL**	**Beijing, CN**	**Grand Central, SA**	**Sydney, AU**
Avg. % HPS	88	41	95	86	68	63	260	20	1.0	20
Avg. % LED	39	18	42	38	30	28	116	9.0	0.0	9.0
Avg. HPS/LED Ratio	2.25									

Table 4.5 – LED heating penalty as a result of switching from High-Pressure Sodium to Light-Emitting Diode fixtures by Location.

	LED Penalty Calculation (kWh/m²y)									
	Athens, GA	**Casper, WY**	**Columbus, OH**	**Montpelier, VT**	**Phoenix, AZ**	**Redmond, OR**	**Arcen, NL**	**Beijing, CN**	**Grand Central, SA**	**Sydney, AU**
LED Penalty	29.62	39.58	63.66	81.91	8.68	55.87	87.46	18.81	0.56	18.84
	LED Penalty as Percentage of Total Heating Load (%)									
	Athens, GA	**Casper, WY**	**Columbus, OH**	**Montpelier, VT**	**Phoenix, AZ**	**Redmond, OR**	**Arcen, NL**	**Beijing, CN**	**Grand Central, SA**	**Sydney, AU**
% of Heat Load	49	23	53	48	38	35	77	15	2.0	109
Avg. LED Penalty	40.50	**Avg. % of Heating Load**	45%							

Tables 4.4 and 4.5 contain data for comparing the amount of nighttime heating provided by HPS lamp configurations to the amount of nighttime heating provided by LED lamp configurations. HPS lamp configurations provide an average of 2.25 times more heat, at an average of 40.5 more kWh/m^2 of nighttime heating, annually. Across all regions, an overall

average of 45% of required nighttime heating is lost when LED lamps are used in place of HPS lamps. One observation is that the penalty for using LED lamps over HPS lamps is larger in colder regions, but the percentage of LED penalty to total heating load varies across regions and cannot necessarily be predicted by location. This could be because colder regions require a much higher magnitude of heating regardless of the lamp type due to the cold temperatures resulting with the heating lost from the lamp conversion less statistically significant.

Thermal Stratification Findings

Two cross-sections of each greenhouse results were saved for viewing the cross-section of the lamps and a cross-section of the middle of the greenhouse where the highest point is. For each lamp type, there is a cross section of the greenhouse orthogonal to the lamps and a cross section of the greenhouse orthogonal to the middle of the gable. The lamp cross section shows the temperature of the lamp along with its immediate surroundings. The scales are user-defined to show the same range for each lamp type. Two walkways were included between the benches to show the depth of penetration towards the ground from the lamps' intensities. This is important to see the full range of thermal stratification. The temperature ranges chosen for each cross-section are the same for each lighting type so an accurate comparison can be made.

The results of the CFD study were in-line with the results found in the heating contribution study. Overall, the HPS lamps released much more heat into the model greenhouse. This is evident from figures 4.1 – 4.4. The lamps appear to be the same temperature because the temperature scale is not a true scale. However, the scales show the temperature contours across the greenhouse environment. These contours represent the thermal stratification – the result of heated air distributing itself in layers. Note in Figures 4.1 – 4.4 that two of the benches were removed from analysis to demonstrate aisleways.

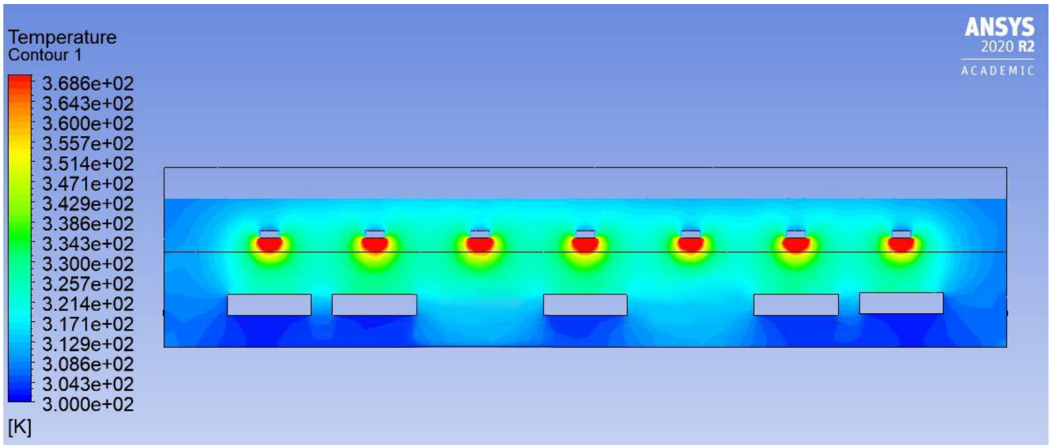


Figure 4.1 – Results from High-Pressure Sodium (HPS) Model – Cross-Section 1 (lamp plane).

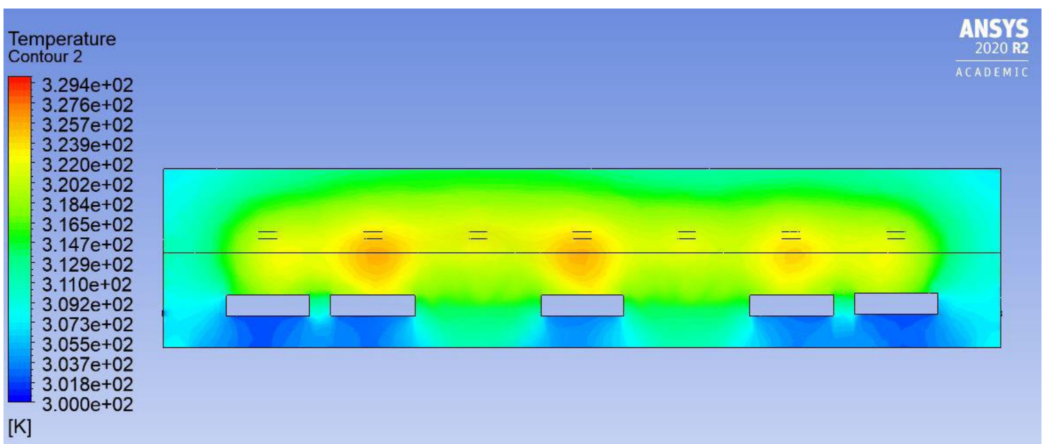


Figure 4.2 – Results from High-Pressure Sodium (HPS) Model – Cross-Section 2 (ridge plane).

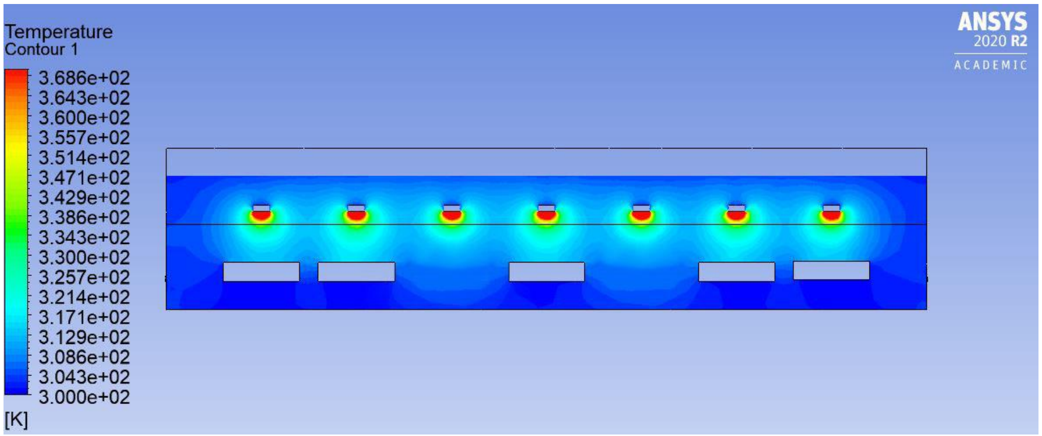


Figure 4.3 – Results from Light-Emitting Diode (LED) Model – Cross-Section 1 (lamp plane).

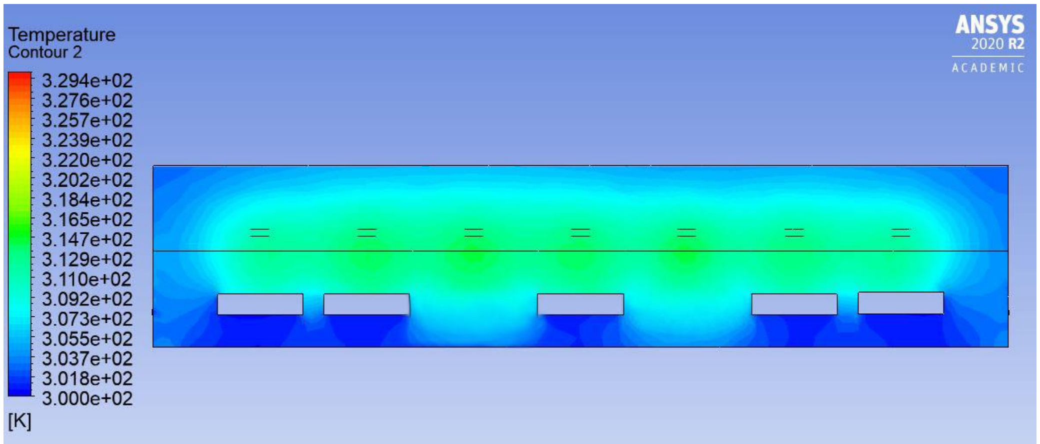


Figure 4.4 – Results from Light-Emitting Diode (LED) Model – Cross-Section 2 (ridge plane).

Comparing Cross-Section 1 (Figures 4.1 and 4.3) between the lamp types, there is a clear contrast in thermal energy present in the greenhouse. This can be seen by comparing the temperature gradients for the HPS lamps and LED lamps. In Figure 4.1, the heated region around the HPS lamps has an average temperature of approximately 330 K (57°C). In Figure 4.3**,** the heated region around the LED lamps remains unblended and there is cooler air in between the lamps with a temperature of approximately 310 K (37°C).

Comparing Cross-Section 2 (Figures 4.2 and 4.4) for the two lamp types, the temperature distribution across the center plane of the greenhouse can be seen. These figures show the cross-section orthogonal to the ridge of the gable between rows of lamps. In the HPS greenhouse shown in Figure 4.2, there are regions with higher temperatures in line with the lamp locations. Looking up towards the ridge, there is hot air trapped at the peak of the greenhouse with a temperature of approximately 315 K (38°C) in the HPS greenhouse and 305 K (32°C) in the LED greenhouse.

Linear Regression

Across all locations investigated, a distinctively higher magnitude of heating load was left to the greenhouse heating system when the LED configurations were implemented versus the HPS configurations (Figure 4.5). As presented, this LED “penalty” that represents the amount of heating lost by using LED lamps instead of HPS lamps was averaged at 40.5 kWh/m^2y, with the highest penalties being in Arcen, the Netherlands and Montpelier, VT. These two cities are required the most hours of supplemental lighting, respectively by LED penalty. On the obverse, the two cities that resulted with the lowest LED penalties were Phoenix, AZ and Grand Central, South Africa. These cities had the least hours of supplemental lighting, respectively by LED penalty. Another observation is that the percentage of the heating load that corresponds to the LED penalty varies by a different pattern. Although the extreme cases (Arcen and Grand Central) seem to follow the direct correlation pattern between LED penalty and percentage of heating load, this does not hold true for all locations. For example, the LED penalty values for Athens, GA and Montpelier, VT were very different. Montpelier’s LED penalty was nearly three times that of Athens, GA (81.91 kWh/m^2 and 29.62 kWh/m^2 respectively), but the percentages of the total heating load these LED penalty values accounted for were very close between the two locations, Athens, GA with 49% and Montpelier, VT with 48%. This can be explained because the Montpelier, VT location had a much higher annual nightly heating requirement but suggests that for some colder climates the decision on which lighting system to implement may not be so simple. Remember, Arcen resulted with a similar LED penalty value to Montpelier, VT, but this accounted for 77% of the heating load in Arcen, the Netherlands. There are other predictors than total heating load (which is inherently linked to outdoor temperatures) that need to be considered to compare the effects of the two different supplemental lighting systems.

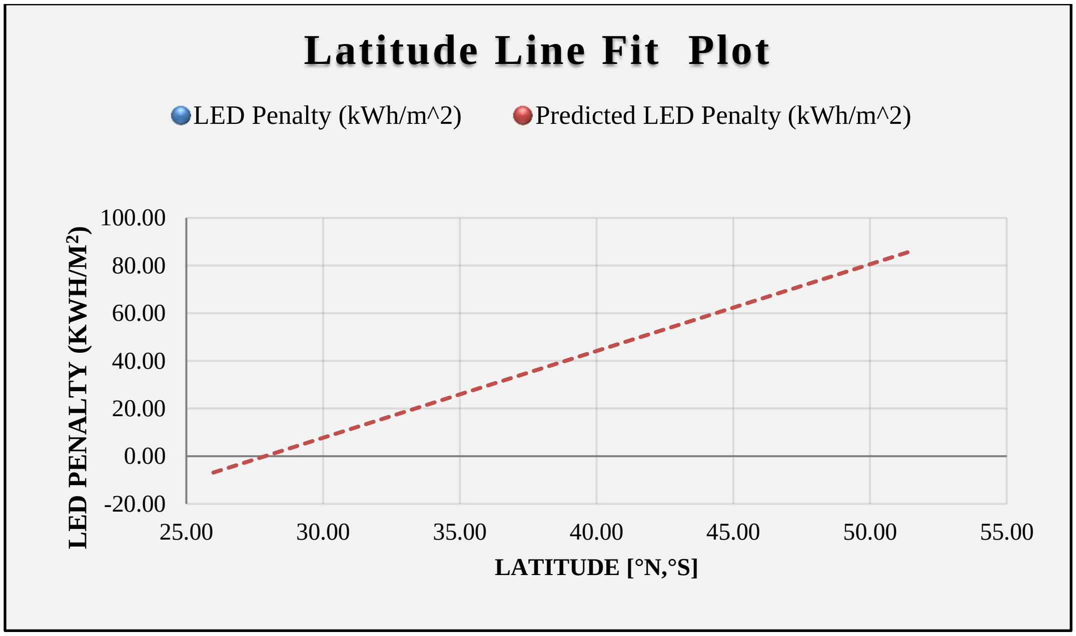
Linear regression is a simple method of finding how much one data set can explain another. In the context of this study, the goal was to figure out how to predict the LED penalty by location using a number of predictors. This way, greenhouse operators can use a number of climate and location data to aid in the decision regarding which type of supplemental lighting to use. The predictors used are familiar to the concepts discussed in this study and are technically proxies to the data collected. The predictors used in this study are the Latitude of each location, annual Heating Degree Days of each location, and the annual amount of PAR delivered by the sun for each Typical Meteorological year for each location.

Table 4.6 – Predictors by Location.

Location	Latitude [°N,°S]	Sun Photosynthetically Active Radiation [mol/m^2]	Heating Degree Days [°F]	LED Penalty (kWh/m^2)
Athens, GA	33.95	9598	2755	29.62
Casper, WY	42.85	9397	7308	39.58
Columbus, OH	39.96	7773	5450	63.66
Montpelier, VT	44.26	7030	7227	81.91
Phoenix, AZ	33.45	12183	912	8.68
Redmond, OR	44.27	9247	6418	55.87
Arcen, NL	51.48	7610	5193	87.46
Beijing, CN	39.90	10264	5121	18.81
Grand Central, SA	25.99	12617	1796	0.56
Sydney, AU	33.87	9849	1205	18.84

The latitude of each location was chosen as a predictor to test how well the distance from the equator explained the LED penalty results. This may be more of an obvious one, essentially testing the idea that locations further from the equator are colder and require more heating. The Heating Degree Day values are the annual sum of Heating Degree Days from every day of the year for each respective location. Heating Degree Days are calculated by taking the low temperature of each day and subtracting it from 65°F. Using this annual predictor will test how well the total amount of heating defined by temperature difference will explain the LED penalty results for each location. The Sun PAR data was calculated using the Typical Meteorological Year data and summing up the the PAR delivered by the sun each day. Sun PAR is separated heating requirement data, making it more likely to correlate with the amount of lighting required at each location.

Four different linear regression analyses were performed, one multiple regression analysis with all three predictors, and three simple linear regression analyses were performed testing one predictor each. Since there are only ten data points, all regression analyses were performed in Microsoft Excel using the Data Analysis feature.



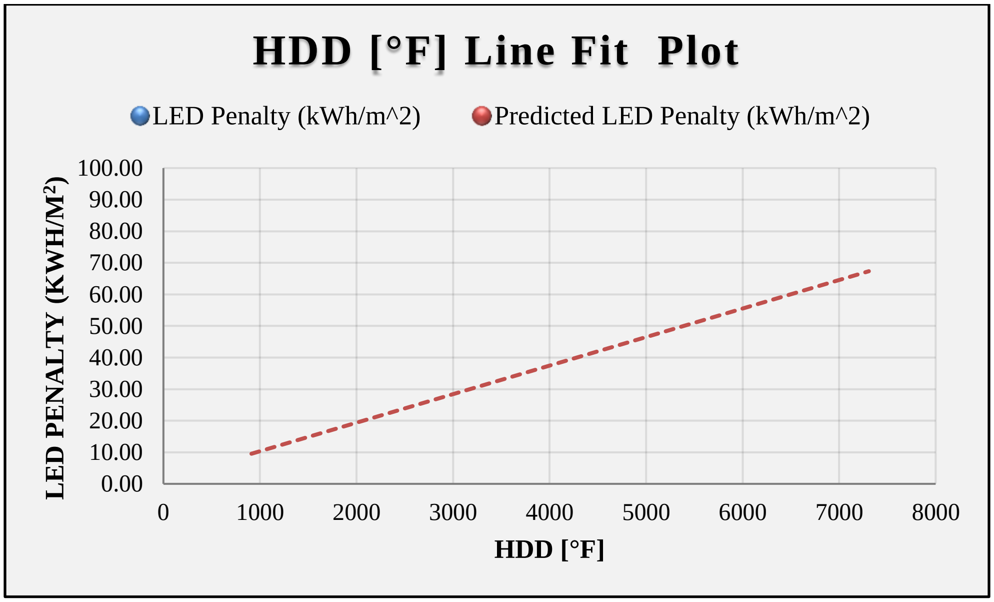
Regression Statistics	
Multiple R	0.872171
R Square	0.760682
Adjusted R Square	0.730767
Standard Error	15.81308
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6358.432	6358.432	25.42829	0.0009983
Residual	8	2000.427	250.0534		
Total	9	8358.859			

Figure 4.5 – Results of the linear regression for latitude.

Latitude outperformed expectations as a predictor, with an R^2 value of 0.76, the data proved to be statistically significant with a P value of 9.98×10^{-4}.



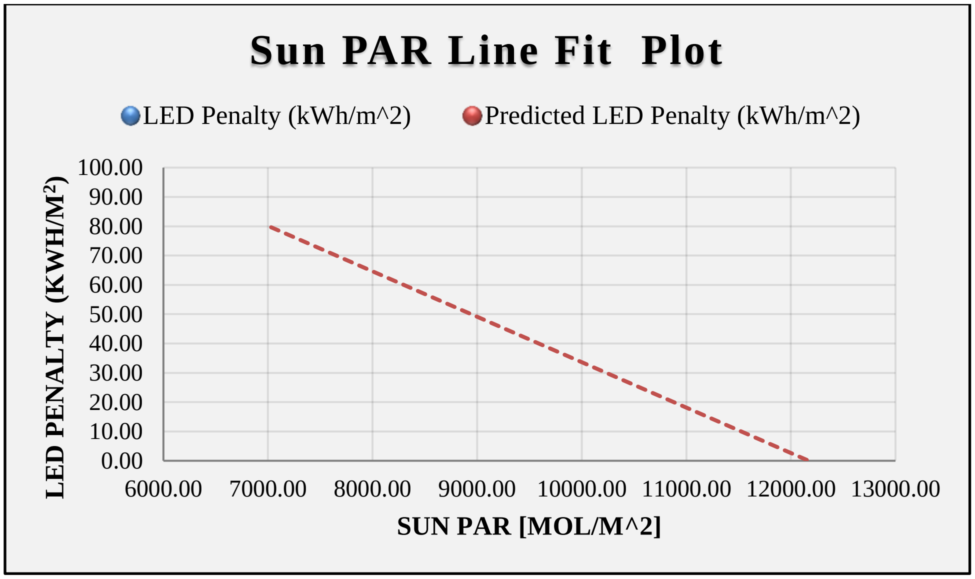
Regression Statistics	
Multiple R	0.730379
R Square	0.533453
Adjusted R Square	0.475135
Standard Error	22.07883
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	4459.06	4459.06	9.147263	0.016448
Residual	8	3899.799	487.4748		
Total	9	8358.859			

Figure 4.6 – Results of the linear regression for Heating Degree Days.

Heating Degree Days performed the worst as a predictor for LED penalty. The R^2 value was 0.53 with a P-Value of 0.01645. This meets the qualification for statistically significant (<0.05).



Regression Statistics	
Multiple R	0.933255
R Square	0.870964
Adjusted R Square	0.854835
Standard Error	11.61138
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	7280.266	7280.266	53.99	8.01E-05
Residual	8	1078.593	134.8242		
Total	9	8358.859			

Figure 4.7 – Results of the linear regression for Sun Photosynthetically Active Radiation

Sun PAR proved to be the best predictor out of the three, as might be expected since that is a dominate factor. The R^2 value was 0.87 with a P-value of $8x10^{-5}$.

Regression Statistics	
Multiple R	0.955552
R Square	0.913079
Adjusted R Square	0.869619
Standard Error	11.00422
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	7632.302528	2544.100843	21.00951	0.001388
Residual	6	726.556635	121.0927725		
Total	9	8358.859163			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	88.66694	61.9500	1.43126	0.20231	-62.919	240.253	-62.91	240.25
Sun PAR	-0.01102	0.00347	-3.1741	0.0192	-0.0195	-0.0025	-0.019	-0.0025
Latitude	1.503043	0.96852	1.55189	0.1716	-0.8668	3.87293	-0.866	3.8729
HDD [°F]	-0.00034	0.00245	-0.1398	0.89331	-0.0063	0.00566	-0.006	0.0056

Figure 4.8 – Results of the multiple regression for Sun Photosynthetically Active Radiation, Latitude, and Heating Degree Days.

The multiple regression results were interesting in that the predictors behaved very differently from the simply linear regression. The only significant predictor was the Sun PAR with a P-value of 0.0192. Together, all three predictors were able to explain 91.3% of the LED penalty data, but with very high error for the Latitude predictor and only one significant predictor. This is most likely due to correlation between predictors. It makes sense that the Sun PAR would stand apart because it is not a result outdoor temperature, whereas Latitude and HDD are highly correlated in that colder climates are in higher latitudes. The amount of sunlight, as seen with the study with Montpelier, VT and Arcen, the Netherlands can vary widely even between climates that require high amounts of heating.

CHAPTER 5

CONCLUSIONS

Significance of Findings

The results of the heating contribution study and the LED penalty findings agree with the existing research summarized in the literature review. In every case presented, the HPS lamp configurations contributed more heat energy to the growing area with an average of 2.25 times more heat contributed. For some locations, these heating ratios corresponded with a much larger LED penalty. This means that a significant amount of heating that otherwise was delivered by the HPS lamps had to be provided by the greenhouse heating system. Looking at the locations individually, this penalty varied widely. The LED penalty was highest in regions where a lot of lighting is required. However, it did not necessarily correlate with locations with higher annual nightly heating loads. Locations with similar LED penalties, such as Montpelier, VT and Arcen, NL, saw this value attribute to very different percentages of the annual nightly heating load. These results suggest that the amount of supplemental lighting required is the largest factor in determining the significance of the LED penalty value. This finding is confirmed when looking at the regression analysis results.

When considering the results of the regression analyses, there are a few things to keep in mind. No one predictor was able explain 100% of the data, and weather conditions vary wildly by location, even at similar latitudes. This is important information for greenhouse operators to know when considering which type of supplemental lighting systems to implement. Where

Katzin et al. (2020) found that supplemental lighting can impact heating load, this study identified other variables that influence the significance of that impact. Not only do the lamp specifications and number of lamps matter, but the amount of time that the lamps are on, which is influenced by the amount of PAR received by sunlight, matters greatly. Cold climates can vary widely in the amount of sunlight received. This means that, when comparing the percentages of LED penalty to annual nightly heating load, locations where greenhouses require a lot of supplemental lighting (i.e., the Netherlands) can be negatively affected by a change in lighting type, and locations that require a lot of heating (i.e., Vermont) can justify the cost of LED conversion with the same metric as a greenhouse operation in a mild climate like Athens, GA. In other words, LED penalty significance is not solely related to heating load or lighting requirements.

A portion of this study was dedicated to looking at the effects supplemental lighting type on thermal stratification. As has been discussed, this is a large factor in greenhouse costs due to the amount of heat that needs to be removed from greenhouses when thermal energy accumulates above the crop canopy. Other studies such as Kittas et al. (2002) and Li and Willits (2008) studied thermal stratification in greenhouses above the canopy but did not consider the impact of lighting type. This study put a magnifying glass on the lighting impacts by implementing a CFD analysis to reach steady state with only lamps in the greenhouse. The results showed large disparities in air temperatures throughout the greenhouse, with a 20°C difference in the region around the lamps between the two scenarios. The radiative heat from the HPS lamps created thermally insulated regions of heated air above the crop canopy approximately 10°C higher in temperature than the LED lamps. This higher temperature air would either be utilized to supplement the space heating system, contribute to a cooling load, or need to be removed via ventilation if possible. This further supports the case that locations with low LED penalties might want to consider the switch to LED supplemental lighting systems because if they do not need the extra heating from the lamps then they will have to spend resources to remove the excess heat.

CHAPTER 6

FINAL REMARKS

Broader Impacts

The purpose of studying the heating contribution differentials between traditional lamp technologies (HPS) and their innovative alternatives (LED) is immediately helpful for those seeking to decrease energy costs for greenhouse operations. However, there are other impacts to consider. The global agriculture industry is dependent on greenhouses. This is true for crop production across every market and is especially true for locations where greenhouses are used for food production. In many areas of the world, food is a scarce resource due of many reasons such as demand, climate conditions, or both. By decreasing the overhead costs such as lighting and heating, greenhouses can provide cheaper and more affordable crops of all varieties, including food, to consumers.

Recommendations

It is suggested that greenhouse operators perform adequate research before making changes to the type of supplemental lighting they select. To ensure that a change to an alternate form of supplemental lighting is justifiable, multiple variables should be researched that are particular to the specific location, growing space, lighting, and heating requirements of the crop. Specifically, the results of this study emphasize that the amount of supplemental lighting required is the most important indicator for determining the impact on heating costs of a lighting change. This study did not attempt to place a monetary value on the LED penalty values to determine significance, this is due to the inconsistency of energy costs across different regions and countries. However, greenhouse operators can make use of the LED penalty calculated for their location and apply their local electricity costs to determine significance of LED penalty to space heating costs.

This study also found conclusions regarding the effect of HPS and LED lighting on thermal stratification. HPS lamps contributed more to the accumulation of thermal energy into the greenhouse, specifically above the canopy where air can be trapped, and humidity can rise. Greenhouse operators need to be especially aware of this effect if they are in hot or humid climates or have ventilation systems that cannot handle the removal of large amounts of excess heat. It was found in the literature that mechanical ventilation systems that utilize horizontal air flow fans can help mitigate this accumulation of thermal energy, but this is not practical for larger commercial greenhouses or when the temperature is too high (~27°C and higher). Air conditioning units and/or dehumidifiers may need to be introduced to assist in these extreme cases.

Virtual Grower is a tool that is already used widely by greenhouse operators, however there are ways of improving its algorithm to yield more accurate heating costs. The lighting arrangement feature should contribute to the energy balance inside the greenhouse, causing a resulting change to the heating requirements. This change will allow greenhouse operators to obtain results that more accurately depict their specific growing system.

Future Studies

There is still much to learn about the consequences of converting from HPS to LED lighting systems. The scope of this study was to find a metric for comparing these consequences regarding greenhouse heating load, but there are countless variables that can be added or altered to learn more. For the simulations, the lamps' heating capacities were restricted by a conversion efficiency that was based in the literature. However, even desired light that is within the conversion efficiency (usable PAR, not considered wasted energy) will eventually degrade to heat energy. It is true that some portion of this energy, possibly around 5%, will leave the greenhouse, however, the inclusion of some of this light within the range of conversion efficiency in the heating study might prove to be more accurate in further research. Also, it is known from the literature that HPS lamps emit a large amount of low-wave radiation, unlike LED lamps. This suggests that the heating contributed by LEDs is predominantly through convection instead of radiation like HPS lamps. These distinctions were not included in this study outside of general energy balance based on electric input. Therefore, a study that observes these differences in heat transfer might find some enlightening results. The CFD model in this study was kept simple and restricted to observe a steady-state snapshot comparison between the two lighting types. The only differences between the lamp systems were the wattages, so the results may not be representative for a true "typical" greenhouse. Lighting arrangements are, in actuality, designed to optimize light intensity. Therefore, testing different numbers of lamps based on production goals could yield more pertinent information for growers across different locations. In both the CFD and heating studies, the addition of combination lighting configurations involving mixtures of lamp types could also yield useful data. This practice was found to be common through literature as a way of lowering electricity costs, minimize heat gain, and optimize light intensity.

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Appendix A

Engineering Equation Solver Output Table

Parametric Table: Table 1

	$T_{outside}$ [K]	T_{diff} [K]	T_{bulk} [K]	T_{plants} [K]	$Heat_{amount}$ [thm]	$Heat_{cost}$ [dollars]
Run 1	244	58.28	235.7	236.6	0.5968	0.5968
Run 2	245.6	56.35	237.7	238.5	0.577	0.577
Run 3	247.1	54.41	239.6	240.4	0.5571	0.5571
Run 4	248.7	52.46	241.5	242.4	0.5372	0.5372
Run 5	250.2	50.51	243.5	244.3	0.5172	0.5172
Run 6	251.8	48.55	245.4	246.2	0.4972	0.4972
Run 7	253.3	46.59	247.4	248.1	0.4771	0.4771
Run 8	254.9	44.63	249.4	250.1	0.457	0.457
Run 9	256.4	42.65	251.3	252	0.4368	0.4368
Run 10	258	40.68	253.3	253.9	0.4165	0.4165
Run 11	259.5	38.69	255.3	255.9	0.3962	0.3962
Run 12	261.1	36.71	257.3	257.8	0.3759	0.3759
Run 13	262.6	34.71	259.3	259.7	0.3555	0.3555
Run 14	264.2	32.71	261.3	261.7	0.335	0.335
Run 15	265.7	30.71	263.3	263.6	0.3145	0.3145
Run 16	267.3	28.7	265.3	265.6	0.2939	0.2939
Run 17	268.8	26.68	267.3	267.5	0.2732	0.2732
Run 18	270.4	24.66	269.3	269.5	0.2525	0.2525
Run 19	271.9	22.63	271.4	271.4	0.2318	0.2318
Run 20	273.5	20.6	273.4	273.4	0.2109	0.2109
Run 21	275	18.56	275.4	275.4	0.1901	0.1901
Run 22	276.6	16.52	277.5	277.3	0.1691	0.1691
Run 23	278.1	14.46	279.5	279.3	0.1481	0.1481
Run 24	279.7	12.41	281.6	281.3	0.1271	0.1271
Run 25	281.2	10.34	283.7	283.2	0.1059	0.1059
Run 26	282.8	8.275	285.7	285.2	0.08473	0.08473
Run 27	284.3	6.199	287.8	287.2	0.06348	0.06348
Run 28	285.9	4.117	289.9	289.2	0.04216	0.04216
Run 29	287.4	2.029	292	291.2	0.02078	0.02078
Run 30	289	-0.06571	294.1	293.2	-0.0006729	-0.0006729
Run 31	290.5	-2.167	296.2	295.1	-0.02219	-0.02219
Run 32	292.1	-4.274	298.3	297.1	-0.04377	-0.04377
Run 33	293.6	-6.388	300.4	299.1	-0.06542	-0.06542
Run 34	295.2	-8.509	302.5	301.1	-0.08713	-0.08713
Run 35	296.7	-10.64	304.6	303.1	-0.1089	-0.1089
Run 36	298.3	-12.77	306.8	305.1	-0.1308	-0.1308
Run 37	299.8	-14.91	308.9	307.1	-0.1527	-0.1527
Run 38	301.4	-17.06	311.1	309.1	-0.1747	-0.1747
Run 39	302.9	-19.21	313.2	311.1	-0.1968	-0.1968
Run 40	304.5	-21.38	315.4	313.1	-0.2189	-0.2189
Run 41	306	-23.54	317.5	315.2	-0.2411	-0.2411
Run 42	307.6	-25.72	319.7	317.2	-0.2634	-0.2634
Run 43	309.1	-27.9	321.9	319.2	-0.2857	-0.2857
Run 44	310.7	-30.09	324.1	321.2	-0.3082	-0.3082
Run 45	312.2	-32.29	326.3	323.2	-0.3307	-0.3307
Run 46	313.8	-34.5	328.5	325.2	-0.3532	-0.3532
Run 47	315.3	-36.71	330.7	327.3	-0.3759	-0.3759
Run 48	316.9	-38.93	332.9	329.3	-0.3986	-0.3986
Run 49	318.4	-41.16	335.2	331.3	-0.4215	-0.4215
Run 50	320	-43.39	337.4	333.3	-0.4443	-0.4443

Formatted Equations

Wall 1:

$$\dot{Q}_{conv,wall1,to,bulk} = U_{wall} \cdot A_{wall1} \cdot (T_{wall1} - T_{bulk})$$

$$\dot{Q}_{rad,wall1,to,ground} = \sigma \cdot E_{wall} \cdot A_{wall1} \cdot F_{wall,to,ground,S} \cdot (T_{wall1}^{4} - T_{ground}^{4})$$

$$\dot{Q}_{conv,wall1,to,outside} = U_{wall} \cdot A_{wall1} \cdot (T_{wall1} - T_{outside})$$

$$\dot{Q}_{rad,wall1,to,out,ground} = \sigma \cdot E_{wall} \cdot A_{wall1} \cdot F_{wall,to,ground,S} \cdot (T_{wall1}^{4} - T_{outside,ground}^{4})$$

$$\dot{Q}_{rad,wall1,to,roof} = \sigma \cdot E_{wall} \cdot A_{wall1} \cdot F_{wall,to,roof} \cdot (T_{wall1}^{4} - T_{roof}^{4})$$

$$\dot{Q}_{rad,wall1,to,sky} = \sigma \cdot E_{wall} \cdot A_{wall1} \cdot F_{wall,to,sky} \cdot (T_{wall1}^{4} - T_{outside}^{4})$$

$$\dot{Q}_{conv,wall1,to,bulk} + \dot{Q}_{rad,wall1,to,ground} + \dot{Q}_{conv,wall1,to,outside} + \dot{Q}_{rad,wall1,to,out,ground} + \dot{Q}_{rad,wall1,to,roof} + \dot{Q}_{rad,wall1,to,sky} = 0$$

Wall 2:

$$\dot{Q}_{conv,wall2,to,bulk} = U_{wall} \cdot A_{wall2} \cdot (T_{wall2} - T_{bulk})$$

$$\dot{Q}_{rad,wall2,to,ground} = \sigma \cdot E_{wall} \cdot A_{wall2} \cdot F_{wall,to,ground,S} \cdot (T_{wall2}^{4} - T_{ground}^{4})$$

$$\dot{Q}_{conv,wall2,to,outside} = U_{wall} \cdot A_{wall2} \cdot (T_{wall2} - T_{outside})$$

$$\dot{Q}_{rad,wall2,to,out,ground} = \sigma \cdot E_{wall} \cdot A_{wall2} \cdot F_{wall,to,ground,S} \cdot (T_{wall2}^{4} - T_{outside,ground}^{4})$$

$$\dot{Q}_{rad,wall2,to,roof} = \sigma \cdot E_{wall} \cdot A_{wall2} \cdot F_{wall,to,roof} \cdot (T_{wall2}^{4} - T_{roof}^{4})$$

$$\dot{Q}_{rad,wall2,to,sky} = \sigma \cdot E_{wall} \cdot A_{wall2} \cdot F_{wall,to,sky} \cdot (T_{wall2}^{4} - T_{outside}^{4})$$

$$\dot{Q}_{conv,wall2,to,bulk} + \dot{Q}_{rad,wall2,to,ground} + \dot{Q}_{conv,wall2,to,outside} + \dot{Q}_{rad,wall2,to,out,ground} + \dot{Q}_{rad,wall2,to,roof} + \dot{Q}_{rad,wall2,to,sky} = 0$$

Wall 3:

$$\dot{Q}_{conv,wall3,to,bulk} = U_{wall} \cdot A_{wall3} \cdot (T_{wall3} - T_{bulk})$$

$$\dot{Q}_{rad,wall3,to,ground} = \sigma \cdot E_{wall} \cdot A_{wall3} \cdot F_{wall,to,ground,L} \cdot (T_{wall3}^{4} - T_{ground}^{4})$$

$$\dot{Q}_{conv,wall3,to,outside} = U_{wall} \cdot A_{wall3} \cdot (T_{wall3} - T_{outside})$$

$$\dot{Q}_{rad,wall3,to,out,ground} = \sigma \cdot E_{wall} \cdot A_{wall3} \cdot F_{wall,to,ground,L} \cdot (T_{wall3}^{4} - T_{outside,ground}^{4})$$

$$\dot{Q}_{rad,wall3,to,roof} = \sigma \cdot E_{wall} \cdot A_{wall3} \cdot F_{wall,to,roof} \cdot (T_{wall3}^{4} - T_{roof}^{4})$$

$$\dot{Q}_{rad,wall3,to,sky} = \sigma \cdot E_{wall} \cdot A_{wall3} \cdot F_{wall,to,sky} \cdot (T_{wall3}^{4} - T_{outside}^{4})$$

$$\dot{Q}_{conv,wall3,to,bulk} + \dot{Q}_{rad,wall3,to,ground} + \dot{Q}_{conv,wall3,to,outside} + \dot{Q}_{rad,wall3,to,out,ground} + \dot{Q}_{rad,wall3,to,roof} + \dot{Q}_{rad,wall3,to,sky} = 0$$

Wall 4

$$\dot{Q}_{conv,wall4,to,bulk} = U_{wall} \cdot A_{wall4} \cdot (T_{wall4} - T_{bulk})$$

$$\dot{Q}_{conv,wall4,to,outside} = U_{wall} \cdot A_{wall4} \cdot (T_{wall4} - T_{outside})$$

$$\dot{Q}_{rad,wall4,to,out,ground} = \sigma \cdot E_{wall} \cdot A_{wall4} \cdot F_{wall,to,ground,L} \cdot (T_{wall4}^{4} - T_{outside,ground}^{4})$$

$$\dot{Q}_{rad,wall4,to,roof} = \sigma \cdot E_{wall} \cdot A_{wall4} \cdot F_{wall,to,roof} \cdot (T_{wall4}^{4} - T_{roof}^{4})$$

$$\dot{Q}_{rad,wall4,to,sky} = \sigma \cdot E_{wall} \cdot A_{wall4} \cdot F_{wall,to,sky} \cdot (T_{wall4}^{4} - T_{outside}^{4})$$

$$\dot{Q}_{conv,wall4,to,bulk} + \dot{Q}_{rad,wall4,to,ground} + \dot{Q}_{conv,wall4,to,outside} + \dot{Q}_{rad,wall4,to,out,ground} + \dot{Q}_{rad,wall4,to,roof} + \dot{Q}_{rad,wall4,to,sky} = 0$$

Ground

$$\dot{Q}_{conv,ground,to,bulk} = U_{ground} \cdot A_{ground} \cdot (T_{ground} - T_{bulk})$$

$$\dot{Q}_{rad,ground,to,wall1} = \sigma \cdot E_{ground} \cdot A_{ground} \cdot \left[\frac{F_{wall,to,ground,S} + F_{wall,to,ground,L}}{2}\right] \cdot (T_{ground}^{4} - T_{wall1}^{4})$$

$$\dot{Q}_{rad,ground,to,wall2} = \sigma \cdot E_{ground} \cdot A_{ground} \cdot \left[\frac{F_{wall,to,ground,S} + F_{wall,to,ground,L}}{2}\right] \cdot (T_{ground}^{4} - T_{wall2}^{4})$$

$$\dot{Q}_{rad,ground,to,wall3} = \sigma \cdot E_{ground} \cdot A_{ground} \cdot \left[\frac{F_{wall,to,ground,S} + F_{wall,to,ground,L}}{2}\right] \cdot (T_{ground}^{4} - T_{wall3}^{4})$$

$$\dot{Q}_{rad,ground,to,wall4} = \sigma \cdot E_{ground} \cdot A_{ground} \cdot \left[\frac{F_{wall,to,ground,S} + F_{wall,to,ground,L}}{2}\right] \cdot (T_{ground}^{4} - T_{wall4}^{4})$$

$$\dot{Q}_{rad,ground,to,roof} = \sigma \cdot E_{ground} \cdot A_{ground} \cdot F_{ground,to,roof} \cdot (T_{ground}^{4} - T_{roof}^{4})$$

$$\dot{Q}_{conv,ground,to,bulk} + \dot{Q}_{rad,ground,to,wall1} + \dot{Q}_{rad,ground,to,wall2} + \dot{Q}_{rad,ground,to,wall3} + \dot{Q}_{rad,ground,to,wall4} + \dot{Q}_{rad,ground,to,roof} = 0$$

Roof

$$\dot{Q}_{conv,roof,to,bulk} = U_{roof} \cdot A_{roof} \cdot (T_{roof} - T_{bulk})$$

$$\dot{Q}_{rad,roof,to,ground} = \sigma \cdot E_{roof} \cdot A_{roof} \cdot F_{ground,to,roof} \cdot (T_{roof}^{4} - T_{ground}^{4})$$

$$\dot{Q}_{conv,roof,to,outside} = U_{roof} \cdot A_{roof} \cdot (T_{roof} - T_{outside})$$

$$\dot{Q}_{rad,roof,to,wall1} = \sigma \cdot E_{roof} \cdot A_{roof} \cdot F_{wall,to,roof} \cdot (T_{roof}^{4} - T_{wall1}^{4})$$

$$\dot{Q}_{rad,roof,to,wall2} = \sigma \cdot E_{roof} \cdot A_{roof} \cdot F_{wall,to,roof} \cdot (T_{roof}^{4} - T_{wall2}^{4})$$

$$\dot{Q}_{rad,roof,to,wall3} = \sigma \cdot E_{roof} \cdot A_{roof} \cdot F_{wall,to,roof} \cdot (T_{roof}^{4} - T_{wall3}^{4})$$

$$\dot{Q}_{rad,roof,to,wall4} = \sigma \cdot E_{roof} \cdot A_{roof} \cdot F_{wall,to,roof} \cdot (T_{roof}^{4} - T_{wall4}^{4})$$

$$\dot{Q}_{rad,roof,to,sky} = \sigma \cdot E_{roof} \cdot A_{roof} \cdot 1 \cdot (T_{roof}^{4} - 273\ [K]^{4})$$

$$\dot{Q}_{rad,wall4,to,ground} = \sigma \cdot E_{wall} \cdot A_{wall4} \cdot F_{wall,to,ground,L} \cdot (T_{wall4}^{4} - T_{ground}^{4})$$

$$\dot{Q}_{conv,roof,to,bulk} + \dot{Q}_{rad,roof,to,ground} + \dot{Q}_{conv,roof,to,outside} + \dot{Q}_{rad,roof,to,wall1} + \dot{Q}_{rad,roof,to,wall2} + \dot{Q}_{rad,roof,to,wall3} + \dot{Q}_{rad,roof,to,wall4} + \dot{Q}_{rad,roof,to,sky} = 0$$

Plants

$$\dot{Q}_{conv,plants,to,bulk} = U_{plants} \cdot A_{plants} \cdot (T_{plants} - T_{bulk})$$

$$\dot{Q}_{rad,plants,to,roof} = \sigma \cdot E_{plants} \cdot A_{plants} \cdot F_{plants,to,roof} \cdot (T_{plants}^{4} - T_{roof}^{4})$$

$$\dot{Q}_{rad,plants,to,wall1} = \sigma \cdot E_{plants} \cdot A_{plants} \cdot F_{plants,to,wall} \cdot (T_{plants}^{4} - T_{wall1}^{4})$$

$$\dot{Q}_{rad,plants,to,wall2} = \sigma \cdot E_{plants} \cdot A_{plants} \cdot F_{plants,to,wall} \cdot (T_{plants}^{4} - T_{wall2}^{4})$$

$$\dot{Q}_{rad,plants,to,wall3} = \sigma \cdot E_{plants} \cdot A_{plants} \cdot F_{plants,to,wall} \cdot (T_{plants}^{4} - T_{wall3}^{4})$$

$$\dot{Q}_{rad,plants,to,wall4} = \sigma \cdot E_{plants} \cdot A_{plants} \cdot F_{plants,to,wall} \cdot (T_{plants}^{4} - T_{wall4}^{4})$$

$$\dot{Q}_{conv,bulk,to,plants} = U_{plants} \cdot A_{plants} \cdot (T_{bulk} - T_{plants})$$

$$\dot{Q}_{conv,plants,to,bulk} + \dot{Q}_{rad,plants,to,roof} + \dot{Q}_{rad,plants,to,wall1} + \dot{Q}_{rad,plants,to,wall2} + \dot{Q}_{rad,plants,to,wall3} + \dot{Q}_{rad,plants,to,wall4} = 0$$

Overall Energy Balance

$$\dot{Q}_{rad,wall1,to,ground} + \dot{Q}_{rad,wall1,to,out,ground} + \dot{Q}_{rad,wall1,to,roof} + \dot{Q}_{rad,wall1,to,sky} + \dot{Q}_{rad,wall2,to,ground} + \dot{Q}_{rad,wall2,to,out,ground} + \dot{Q}_{rad,wall2,to,roof} + \dot{Q}_{rad,wall2,to,sky} + \dot{Q}_{rad,wall3,to,ground} + \dot{Q}_{rad,wall3,to,out,ground} + \dot{Q}_{rad,wall3,to,roof} + \dot{Q}_{rad,wall3,to,sky} + \dot{Q}_{rad,wall4,to,ground} + \dot{Q}_{rad,wall4,to,out,ground} + \dot{Q}_{rad,wall4,to,roof} + \dot{Q}_{rad,wall4,to,sky} + \dot{Q}_{rad,ground,to,wall1} + \dot{Q}_{rad,ground,to,wall2} + \dot{Q}_{rad,ground,to,wall3} + \dot{Q}_{rad,ground,to,wall4} + \dot{Q}_{rad,ground,to,roof} + \dot{Q}_{rad,roof,to,ground} + \dot{Q}_{rad,roof,to,wall1} + \dot{Q}_{rad,roof,to,wall2} + \dot{Q}_{rad,roof,to,wall3} + \dot{Q}_{rad,roof,to,wall4} + \dot{Q}_{rad,plants,to,roof} + \dot{Q}_{rad,plants,to,wall1} + \dot{Q}_{rad,plants,to,wall2} + \dot{Q}_{rad,plants,to,wall3} + \dot{Q}_{rad,plants,to,wall4} - \dot{Q}_{outside,to,bulk} + \dot{Q}_{rad,roof,to,sky} = 0$$

$$\dot{Q}_{outside,to,bulk} = \dot{Q}_{conv,wall1,to,outside} + \dot{Q}_{conv,wall2,to,outside} + \dot{Q}_{conv,wall3,to,outside} + \dot{Q}_{conv,wall4,to,outside} + \dot{Q}_{conv,roof,to,outside} - (\dot{Q}_{conv,wall1,to,bulk} + \dot{Q}_{conv,wall2,to,bulk} + \dot{Q}_{conv,wall3,to,bulk} + \dot{Q}_{conv,wall4,to,bulk} + \dot{Q}_{conv,ground,to,bulk} + \dot{Q}_{conv,roof,to,bulk} + \dot{Q}_{conv,plants,to,bulk})$$

Heat requirement Calculation

$Heat_{unit} = 1$ [dollars/thm] *one therm = 29.3 kWh = 105480000 J*

$Energy_{to,heat} = 0.01024$ [thm/K] *for 765 Kg of Air and Cp = 1.005 kJ/KgK*

$$T_{diff} = T_{req} - T_{bulk}$$

$$Heat_{amount} = T_{diff} \cdot Energy_{to,heat}$$

$$Heat_{cost} = Heat_{unit} \cdot Heat_{amount}$$

Appendix B

MATLAB Code

```
% script to look up TMY3 Nighttime temperatures in EES output table
% Michael Ilardi created 8/26/2020
% Modified by M.I. 11/18/2020

TMY = array2table(xlsread('SydenyAUTMY_No_Light.xlsx')); %Open TMY3 Data and convert
to table
eesnolight = array2table(xlsread('EES_No_Lamp.xlsx')); %Open EES Parametric Table
with No lights & Convert to table

TMY([1,2],:) = [] ; % Delete first two unneccesary rows from data

TMY.Properties.VariableNames([1:9]) = {'Date' 'Hour' 'Toutside' 'ETR' 'ETRN' 'GHI'
'SunDLI' 'LAMPDLI' 'LAMPOnOff'} ; %Set variable names
eesnolight.Properties.VariableNames = {'Toutside' 'Tdiff' 'Tbulk' 'Tplants' 'Hamount'
'Hcost'} ;

TMY.Properties.RowNames = compose('%d', 1:8760) ; %Number Row Names
eesnolight.Properties.RowNames = compose('%d', 1:50) ;


%START OF CODE

lamp = TMY.('LAMPOnOff') ;   %Binary for LED Lamps 0=OFF 1=ON

sun = TMY.('GHI') ;    %Solar Values for per hour nighttime/daytime..... >0 indicates
daytime

ToutTMY = TMY.('Toutside') ; %Outdoor temperatures from TMY3 Data

Touteesnolight = eesnolight.('Toutside') ; %Outdoor temperatures from ees table

heatnolight = eesnolight.('Hamount') ; % heat values from ees table

heatadded1 = 0; %sets total heating term to 0 for while loop

for hour = 1:8760 ;%hour in year (1:8760) ; January (1:744) ; February ( 745:1416)
    hour ;
    lampcurr = lamp(hour) ;
    suncurr = sun(hour) ;
   %Toutcurr = ToutTMY(hour);
    if (suncurr == 0)&(lampcurr == 0)&(ToutTMY(hour) < 294) ; %Checks for hours where
lamps are off BUT heating still needed
        Toutcurr = ToutTMY(hour); %toutside at hour
        if sum(Touteesnolight == Toutcurr) == 1 ; %checks for TMY3 temps that equal
ees temps exactly
            loc = find(Touteesnolight==Toutcurr, 1);
            heatcurr1 = heatnolight(loc);
        else
            i=1 ;
```

```
            Touteescurr = Touteesnolight(i) ; %Gets first value in Toutees
            while Touteescurr < Toutcurr ; %Gets first value larger than Toutcurr
                i = i+1;
                Touteescurr = Touteesnolight(i); %Gets next larger value
            end
            Tupper = Touteesnolight(i); %Location of first value larger
            Tlower = Touteeslight(i-1); % Gets first value smaller
            heatupper = heatnolight(i);
            heatlower = heatnolight(i-1);
            inter = (heatupper - heatlower)/(Toutcurr - Tlower)/(Tupper - Tlower) ;
            heatcurr1 = inter + heatlower
        end
        if heatcurr1 <0 ;
            heatcurr1 = 0 ;
        end
        heatadded1 = heatadded1 + heatcurr1
    end


    heataddedtot = heatadded1 ;

    kWh = heataddedtot * 29.32972 ; % one therm is 29.32972 kWh


end
heataddedtot
    kWh
```

Appendix C

Lighting Configurations

	Efficacy (mol/J)	PPFD (mol/m^{2}s)	Wattage	Plant Area (m^2)	Number of Lamps	Heat Energy from Lamps [W]	DLI Contribution (mol/m^{2}h)
1000W HPS Lamp	1.50E-06	1.00E-04	1000	110	8	6580	0.39
	1.75E-06	1.00E-04	1000	110	7	5758	0.40
	2.00E-06	1.00E-04	1000	110	6	4935	0.39
	2.25E-06	1.00E-04	1000	110	5	4113	0.37
	2.50E-06	1.00E-04	1000	110	5	4113	0.41
	1.50E-06	2.00E-04	1000	110	15	12338	0.74
	1.75E-06	2.00E-04	1000	110	13	10693	0.74
	2.00E-06	2.00E-04	1000	110	11	9048	0.72
	2.25E-06	2.00E-04	1000	110	10	8225	0.74
	2.50E-06	2.00E-04	1000	110	9	7403	0.74
	1.50E-06	3.00E-04	1000	110	22	18095	1.08
	1.75E-06	3.00E-04	1000	110	19	15628	1.09
	2.00E-06	3.00E-04	1000	110	17	13983	1.11
	2.25E-06	3.00E-04	1000	110	15	12338	1.10
	2.50E-06	3.00E-04	1000	110	14	11515	1.15
630W LED Lamp	2.00E-06	1.00E-04	630	110	9	2835	0.37
	2.38E-06	1.00E-04	630	110	8	2520	0.39
	2.75E-06	1.00E-04	630	110	7	2205	0.40
	3.13E-06	1.00E-04	630	110	6	1890	0.39
	3.50E-06	1.00E-04	630	110	5	1575	0.36
	2.00E-06	2.00E-04	630	110	18	5670	0.74
	2.38E-06	2.00E-04	630	110	15	4725	0.73
	2.75E-06	2.00E-04	630	110	13	4095	0.74
	3.13E-06	2.00E-04	630	110	12	3780	0.77
	3.50E-06	2.00E-04	630	110	10	3150	0.72
	2.00E-06	3.00E-04	630	110	27	8505	1.11
	2.38E-06	3.00E-04	630	110	23	7245	1.13
	2.75E-06	3.00E-04	630	110	20	6300	1.13
	3.13E-06	3.00E-04	630	110	17	5355	1.10
	3.50E-06	3.00E-04	630	110	15	4725	1.08

Lighting Requirements

Total Annual Nightly Lighting (hours)									
Athens, GA	Casper, WY	Columbus, OH	Montpelier, VT	Phoenix, AZ	Redmond, OR	Arcen, ND	Beijing, CH	Grand Central, SA	Sydney, AU
846.00	1261.00	1782.00	2248.00	263.00	1620.00	2251.00	678.00	19.00	684.00
839.00	1247.00	1769.00	2242.00	262.00	1612.00	2246.00	660.00	19.00	671.00
846.00	1261.00	1782.00	2248.00	263.00	1620.00	2251.00	678.00	19.00	684.00
851.00	1287.00	1801.00	2268.00	268.00	1637.00	2262.00	708.00	20.00	702.00
835.00	1237.00	1760.00	2229.00	260.00	1601.00	2242.00	653.00	18.00	18.00
665.00	868.00	1438.00	1836.00	192.00	1248.00	2003.00	394.00	11.00	440.00
665.00	868.00	1438.00	1836.00	192.00	1248.00	2003.00	394.00	11.00	440.00
678.00	891.00	1454.00	1872.00	194.00	1273.00	2019.00	403.00	12.00	452.00
665.00	868.00	1438.00	1836.00	192.00	1248.00	2003.00	394.00	11.00	440.00
665.00	868.00	1438.00	1836.00	192.00	1248.00	2003.00	394.00	11.00	440.00
491.00	625.00	1067.00	1399.00	140.00	926.00	1517.00	282.00	9.00	318.00
487.00	618.00	1057.00	1386.00	139.00	915.00	1507.00	280.00	9.00	315.00
484.00	609.00	1038.00	1360.00	137.00	899.00	1480.00	277.00	9.00	309.00
487.00	614.00	1048.00	1371.00	138.00	910.00	1495.00	280.00	9.00	312.00
467.00	591.00	1011.00	1312.00	133.00	869.00	1432.00	269.00	9.00	299.00
851.00	1287.00	1801.00	2268.00	268.00	1637.00	2262.00	708.00	20.00	702.00
846.00	1261.00	1782.00	2248.00	263.00	1620.00	2251.00	678.00	19.00	684.00
839.00	1247.00	1769.00	2242.00	262.00	1612.00	2246.00	660.00	19.00	671.00
846.00	1261.00	1782.00	2248.00	263.00	1620.00	2251.00	678.00	19.00	684.00
854.00	1298.00	1806.00	2281.00	271.00	1642.00	2265.00	718.00	21.00	712.00
665.00	868.00	1438.00	1836.00	192.00	1248.00	2003.00	394.00	11.00	440.00
670.00	877.00	1448.00	1857.00	192.00	1259.00	2009.00	397.00	11.00	446.00
665.00	868.00	1438.00	1836.00	192.00	1248.00	2003.00	394.00	11.00	440.00
650.00	842.00	1398.00	1800.00	185.00	1225.00	1978.00	380.00	11.00	424.00
678.00	891.00	1454.00	1872.00	194.00	1273.00	2019.00	403.00	12.00	452.00
484.00	609.00	1038.00	1360.00	137.00	899.00	1480.00	277.00	9.00	309.00
475.00	602.00	1028.00	1338.00	134.00	886.00	1457.00	274.00	9.00	305.00
475.00	602.00	1028.00	1338.00	134.00	886.00	1457.00	274.00	9.00	305.00
487.00	614.00	1048.00	1371.00	138.00	910.00	1495.00	280.00	9.00	312.00
491.00	625.00	1067.00	1399.00	140.00	926.00	1517.00	282.00	9.00	318.00