Energy Modelling and Analysis of Vertical Farming for Vegetable Production

By

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Abstract

Vertical farming has gained popularity in the last ten years as a potential solution to produce food using minimal resources. A key challenge in vertical farming is intensive energy usage. Limited research exists however on the energy consumption for vertical farming facilities in cold climate conditions. An energy model was developed to estimate the energy consumption for growing lettuce in a small pilot facility. To validate the model, two tests of butter head lettuce, loose leaf lettuce, and kale were grown in the pilot facility. One test occurred from January – February 2024, and the second was in September – October 2024. During the testing period energy usage for the HVAC (heating, ventilation, and air conditioning) system, lighting, irrigation, and IoT sensor and control were recorded and compared with model estimations. The results showed that the two highest energy usages were from lighting and HVAC. Lighting accounted of 46 %– 75% of the total energy consumption, whereas HVAC accounted for 22% - 52%. Overall, it took approximately 29.6 kWh in the winter and 43.9 kWh in the fall to grow looseleaf lettuce for one crop cycle. It was found that less energy was required to operate the SVF in the winter than in the fall due to not requiring cooling during the winter season. The average energy consumption was 451.8 and 676.1 kWh per month for winter and fall, respectively. The energy consumption per m^2 of floor area measured in this study (517.2 - 773 kWh/m^2y) was generally lower than that in different geographic regions reported in the literature (850–1150 kWh/m^2y). The energy model developed in this study performed well for calculating energy consumption by the lighting system (LEDs) but it was less accurate for calculating heating requirements. Overall, the findings from this study proved that vertical farming could be adapted successfully to cold climate regions.

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Dedication

I’d like to dedicate this paper to those who graduate university and want to make a meaningful impact on the world right away. You don’t have to wait ten years to get experience first, you can do it now, just try.

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1.0 Introduction

Global interest in controlled environment agriculture (CEA) is on the rise as a means to provide stability in the food chain. One of the latest developments in CEA is vertical farming (VF) which is the practice of growing crops in vertical layers inside engineered structures (enclosed buildings) where the environment is controlled. By maximizing production space, VF facilities have the capability to grow more produce/ft^2 than traditional field production. For example, a vertical farm opened by Plenty this past year claims to have 350 times the equivalent production as a farm outdoors (Engler, 2021). Additional benefits of vertical farming can also lead to increased food resiliency, decentralized large food production systems, and increased resource use efficiency. Since nearly fifty percent of all habitable land on earth is used for agriculture (Ritchie, 2019), uptake of vertical farming practices in urban cities could result in more land being used for biodiversity restoration purposes.

However, the energy requirements to operate a vertical farm year-round can be high and a barrier to entry (Jaeger, 2024). Additionally, the exact energy requirements for various systems in various regions is still currently ill-defined. There are still gaps in research in properly defining the relationship between energy consumed and crop yield, as the environment plants grow in changes hourly (Keyvan, 2024). Ultimately, dynamic models are required to be developed as change to a number of variables (temperature, humidity, light intensity, airflow and carbon dioxide concentration) affect both the energy consumed and the growth rate of plants. Lastly, energy consumption has been simulated for vertical farms, but few studies have validated their models through experimental procedures. This thesis focused on exploring the correlation between energy consumption and vegetable production at environmental conditions through both modelling and experiments.

2.0 Literature Review

In the process of understanding the current state of research involving vertical farm designs a literature review was conducted. There were two main focuses of this literature review – the relationship between the environment and plant growth, and the relationship between energy usage and creating an optimal growth environment.

Part of the reason why CEA facilities allow for accelerated plant growth is by creating and maintaining optimal conditions for plants. To promote plant growth, factors that influence net photosynthetic rate can be manipulated, including carbon dioxide, temperature, humidity, water and nutrients, and light. When considering creating environments for optimal plant growth, two main topics need to be considered – optimal growth rates, and optimal quality.

Most factors that influence plant growth can be controlled by mechanical equipment in vertical farming, which will have an energy footprint. For example, optimal temperature and humidity conditions are controlled by HVAC systems; water and nutrient delivery is controlled by dosers and pumps; and optimal light intensity and spectrum are achieved through tunable LED grow lights. In this literature review the parameters that influence energy consumption of selected equipment and farm operations were discussed.

To adequately define research gaps in assessing energy consumption of vertical farms, past studies on energy analysis of vertical farms were also reviewed. Studies that influenced the direction of this research paper are highlighted in the review.

2.1 Plant Production Influences

A good baseline indicator of a plant's growth rate is assessing the net photosynthetic rate (NPR). It is important to understand the environmental factors that influences the root and the leaf of the plant in order to determine the overall NPR. As some studies have demonstrated restrictions that occur in the root of a plant will affect the plants overall growth, and yield. (Zakaria, 2020). Photosynthesis occurs in the leaf of a plant and is largely influenced by stomatal conductance (Faralli, 2019). Stomata are molecules at the leaf of the plant which open and close to allow for the plant to release water and uptake gas (Geleen, 2021). Stomatal conductance is the process of the stomata in a plant opening and allowing for transpiration to occur and gas to diffuse into the plant (Faralli, 2019). Essentially, this is the biological mechanism that regulates the photosynthetic reaction (listed below) to occur.

$$6CO_2 + 6H_2O + light \rightarrow C_6H_{12}O_6 + 6O_2 \tag{1}$$

Although photosynthesis occurs in the leaf of the plant, reactions at the roots are equally important, as it regulates water availability in the plant. Cellular respiration occurs at the roots and is the process of root hairs using glucose and oxygen to absorb water and nutrients (Street H.E., 1978). As root hairs absorb water and nutrients, solutes and water are transported using tracheaid vessels of the xylem system in plants. (Taiz, 2002) Xylem fluid travels upward in plants and the velocity of the fluid is governed by the evapotranspiration rate in the plants leaves system (Taiz, 2002) Photosynthesis products (glucose) are transported from the leaves to the roots using the phloem system in plants. (Geleen, 2021). Therefore, the reactions at the leaf and root of the plant need to be considered in conjunction when considering growth rates of the plant.

For example, a study conducted in the Netherlands assessed the difference in relative growth rates and stomatal conductance for cucumber seedlings grown under three different humidity conditions (55%, 75% and 95%) with three different nutrient concentration solutions (1 ds/m, 4 ds/m, 8 ds/m)

(Van de Sanden, 2003). The study found that plant growth rates and stomatal conductance were highest at high humidities with low nutrient concentrations. The main takeaway from this study is that for optimal growth rates, leave environmental conditions (temperature and humidity) had to be considered in conjunction with the root environment (nutrient concentration). (Van de Sanden, 2003). The main factors that influence these reactions include: light, water and nutrients, temperature, humidity, carbon dioxide, oxygen and airflow. A further assessment of how each of these factors influence growth are outlined below.

2.1.1 Light

Light strongly influences the morphology and growth rate of a plant. There are three key factors to consider when developing a light recipe; spectrum, intensity and duration.

2.1.1.1 Spectrum (color)

Photoreceptors are proteins within a plant that are responsible for absorbing light and initiating a cellular response required for growth. (Galvao, 2015). There are five dominant types of photoreceptors in plants including; cryptochromes, phytochromes, phototropins, F-box containing Flavin binding proteins and UVR8. (Paik, 2019). Cryptochromes respond to UV-A/blue light and are responsible for circadian rhythms and controlling cell elongation (Cashmore, 2003). It is popular practice to introduce higher concentrations of blue light during the nursery stage in plants, in order to develop strong stems before cultivation. Phytochromes are responsible for initiating seed germination and flowering – these receptors respond to far red/infra-red light. (Galvao, 2015). Phototropins are responsible for a variety of processes, including regulating stomatal opening' phototropism; and leaf expansion. These photoreceptors respond to blue light (Takemiya, 2005).

In addition to photoreceptors, plants also have photosynthetic pigments which are molecules that absorb light and convert it into energy. (Kraken, 2021) There are two different photo pigments within plants: chlorophyll a and b, and carotenoids (Kraken, 2021). Chlorophyll a and b are responsible for absorbing light and initiating photosynthesis (Kraken, 2021). These two structures have different absorption spectrums (Fig.1).

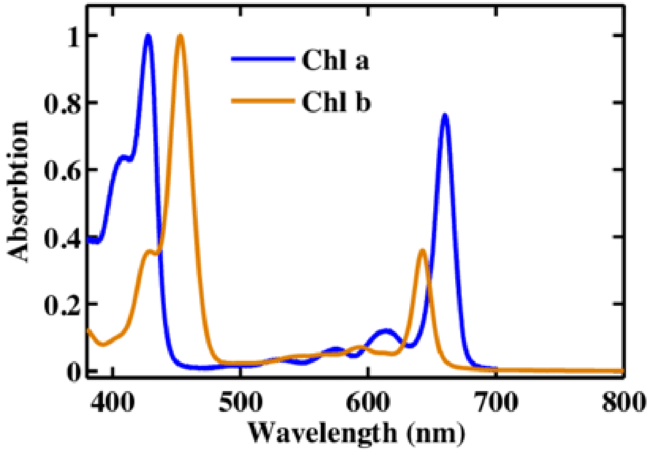


Figure 1. *Absorption Spectrum of Chlorophyll (Mammadov, 2015)*

As seen in the figure, the absorption spectrum for both chlorophyll a & b peaks between 400-500nm (blue light) and 625-675nm (red light). As chlorophyll a & b initiate photosynthesis within the plant, it is important to include red and blue light in light recipes for plants.

Spectrum influences plant species differently — as each variety has an optimal spectrum. This is because each leaf of each plant has millions of photoreceptors — each of which includes specialize pigments which are unique to the plant. (Li, 2022) For example, a review of 319 vertical farming studies conducted by Cynthia Najera, summarized that lemon balm plants, lettuce cultivars and strawberries all had optimal growth under different spectrum recipes (Najera, 2023). Lemon balm plants responded best with a blue, red, green spectra, lettuce cultivars grew larger with far red introduced in the spectrum, and strawberries responded well to red/white combinations. (Najera, 2023).

2.1.1.2 Intensity

Intensity is a measurement of the amount of photosynthetic absorption radiation (PAR) light that shines on a given area for a plant canopy. Intensity is typically measured in units of micro moles of photon per meter squared per second (µmol/m^{2}s) and is referred to as photon photosynthetic flux density (PPFD). Plants have optimal light intensity levels for ideal growing conditions. For example; a study found that leafy greens performed better under intensities lower than 300 umol/m^{2}s as any value higher than that caused tip burn. (Dai, 2024). A separate study measured the plant height and number of leaves for a cultivar of lettuce under light intensities from 120 – 300 umol/m^{2}s (Miao, 2023). In this study, it was found that lettuce grown under light intensities of 120 and 180 µmol/m^{2}s had significantly lower biomass production than those grown at higher intensities (Miao, 2023). Therefore, lower levels of light intensity may impact the overall growth, and too high of intensities can result in tip-burn.

2.1.1.3 Duration

Lighting duration is typically categorized by the photoperiod which indicates the number of hours when light is on vs. the number of hours when light is off in a 24h cycle. Plants have regulated pathways which help them respond to light during the day, and to develop growth hormones at night (Creux, 2019). Thus, it is important, to have a certain number of night hours for a full functioning crop. Plants have optimal ranges of time that they should be exposed to light based on where they naturally grow, and what light is naturally available to them (Dormann, 2020). For instance, increasing the photoperiod for iceberg lettuce had positive effects from 12h to 16h, but negative effects at 20h (Gavhane, 2023).

Total amount of light delivered to a plant canopy overall is measured by the daily light integral (DLI) value. The Ideal DLI targets are an important characteristic to understand the lighting requirement of plants as it combines the optimal intensity and optimal photoperiod. Equation 2 below is used to calculate DLI from photoperiod and light intensity.

$$DLI\left(\frac{mol}{m^2 d}\right) = photoperiod\left(\frac{h}{d}\right) * \ Intensity\ \left(\frac{umol}{m^2 s}\right) * \frac{3600}{100000}\frac{s\ mol}{h\ umol} \tag{2}$$

Suggested DLI values for tomatoes are from 20 - 30 mol/m^2.d in comparison to 14 - 18 for leafy greens (Runkle, 2016.). Studies in the past have proven that alternating the DLI for varieties of leafy greens can cause an increase in shoot fresh and dry mass (Kelly, 2020).

2.1.2 Water and Nutrients

There are at least 14 minerals which are macronutrients and micronutrients that plants require in order for healthy and sustained growth (White, 2010). Macronutrients consist of nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S) and are required in higher amounts (White, 2010). Micronutrients on the other hand consist of chlorine (Cl), boron (B), iron (Fe) manganese (Mn), copper (Cu), Zinc (Zn) and nickel (Ni) and are only required in trace amounts. (White, 2010).

The three most influential minerals are nitrogen, phosphorous and potassium. Nitrogen is required for leaf and stem growth, as plant proteins are built using amino acids (Johnson, 2021). Phosphorous is required for root and seed production, as well as cell wall construction (Johnson, 2021). Lastly potassium is required for the plants vascular system which helps with transporting nutrients from the roots to the leaf of the plant (Johnson, 2021).

In vertical farm set-ups with hydroponic grow systems, nutrient concentration is typically measured by the electrical conductivity (EC) value. This measurement reflects only the total nutrient concentration instead of individual nutrient concentrations. Low EC values can limit crop growth rates, due to nutrient deficiencies (Hosseini, 2021). High EC values however can also be toxic to plants and limit growth rates as well (Hosseini, 2021). A study assessing the dry mass production and growth rates of lettuce and basil found that plants performed best with EC levels of 1.2 and 0.9 dS/m^{-1} (Hosseini, 2021).

Electrical conductivity measurement however is not enough to assess nutrient availability to a plants root system for predicting plant growth rate. The nutrient solution pH must also be equally considered, as it affects the solubility and availability of nutrients (Kudirka, 2023). Usually, the ideal range for most leafy green plants is between 5.5 – 6.5 (Kudirka, 2023). However, there have been studies that show to induce different physiological responses in a plant, a lower pH (such as 4.0) may be beneficial (Kudirka, 2023).

2.1.3 Carbon Dioxide

Carbon dioxide is one of the requirements for photosynthesis. Plants absorb carbon dioxide through the surrounding environment by gas diffusion through opening of stomatal pores (Dashoff, 2022). Carbon dioxide concentrations in the atmosphere are typically low (0.04%), so typically carbon dioxide availability is the limiting factor for plants net photosynthetic rate (Benckiser, n.d.). When carbon dioxide levels are increased, plants are able to produce more glucose and increase the net photosynthetic rate (Thompson, 2017). A study assessing production efficiency of tomato seedlings found that by increasing CO_2 concentrations from 400 to 1000 µmol/mol, the growth rate increased and light was used 38 – 44% more efficiently (Huber, 2021).

Carbon dioxide supplementation however is only effective if all other factors influencing photosynthesis are provided in adequate amounts (Shao, 2021). For instance, if limited light is available, adding CO_2 may not increase the NPR. Additionally, it is important to note that there is a saturation point, where adding more CO_2 will not increase the NPR of a plant. A study demonstrating the carbon dioxide removal potential for indoor office spaces using indoor growing systems found that the saturation point for leafy greens was around 1500ppm. (Shao, 2021).

2.1.4 Temperature, Humidity, and Vapor Pressure Deficit

Temperature has significant effects on crop growth as photosynthesis is highly sensitive to temperature (Moore, 2021). An increase in temperature leads to an increase in the enzyme-driven processes for photosynthesis, up to the inhibition temperature in which photosynthesis then slows down (Moore, 2021). Many studies have shown for example, that the optimal temperature for lettuce to grow in is 17 – 24°C (Hooks, 2022).

Understanding the combined influence of temperature and humidity on plant growth is imperative for successful vertical farming operations. The combination of temperature and relative humidity dictates vapor pressure deficit (VPD) in the air. VPD regulates the opening of plant stomata, which in turn controls the transpiration rate of a plant as well as gas exchange (CO_2) between plant leaves and the atmosphere, and consequently affects nutrient uptake by the roots and photosynthesis (Kuack, 2017).

When VPD is too high (typically hot and dry conditions) than plants can over transpire quickly, causing the stomata to close. This can slow down or stop photosynthesis, reduce nutrient and water uptake, and cause the plant to heat up as it cannot transpire to cool itself down (Kuack, 2017). When VPD is too low, transpiration can be reduced as well, causing insufficient uptake of nutrients (Kuack, n.d.).

The net photosynthetic rate, and nutrient uptake rate of two different tomato cultivars under VPD conditions of 2.2 kPa (high) and 0.9kPa (low) were studied by (Ding, 2022). It was found that one tomato variety showed a higher transpiration rate, and larger uptake of potassium and calcium under high VPD conditions (Ding, 2022). The other variety however had a smaller biomass, and less leaf area under high VPD conditions (Ding, 2022). This study highlighted that even within the same species of plants, VPD conditions might cause different responses depending on the variety. Therefore, when it comes to crop production simulations, VPD conditions must be considered carefully.

2.1.5 Air Flow at Plant Canopy

Airflow at the plant canopy affects the NPR of plants, as it promotes gas exchange between the leaf and its surrounding environment, as well as increases transpiration rates (Kitaya, 2003). If air is stagnant., humidity can be higher and carbon dioxide can be lower around the leaves — eventually leading to mold growth (Burgner, 2021). Lastly, with adequate airflow, plants can build thicker cell walls strengthening their stems (Sabeh, 2025).

The influence of airflow rates on the net photosynthetic rate of various plant species is still being studied. However, one study from 2003, found that transpiration rates of sweet potato leaves increased with varying airflow rates from 0.1m/s up to 1.0 m/s. Net photosynthetic rate however for the same variety only increased until 0.5m/s and remained constant under conditions up to 1.0 m/s (Kitaya, 2003).

2.1.6 Oxygen

Oxygen must be available in the root system for plant growth to occur. Oxygen is required for plants to undergo cellular respiration, allowing for nutrients in the water to dissolve into the root hairs of the plant (Intricare, 2021). In field conditions, oxygen diffuses into soil from the ambient air and is available to plants (Neira, 2015). In certain hydroponic systems however, oxygen diffusion is restricted, as nutrient solutions are contained and covered from the atmosphere (Goto, 1997).

Adding oxygen to a nutrient solution therefore is dependent on the oxygen levels in the water and may not be required. However, studies do report that elevating oxygen levels in the nutrient solution has been linked to increased growth of plants. For instance, lettuce grown using deep water culture hydroponic methods grew 2.1 times larger when treated with 23 mg/L of dissolved oxygen, in comparison to lettuce that was grown under "natural" conditions (Suyantohadi, 2010). Although adding dissolved oxygen may not be necessary, treatments could improve growth rates in certain cases.

2.1.7 Interconnection between Variables

It is equally important to understand how the combination of each independent variable affects plant growth. In an experiment conducted by Milon Chowdhury et.al (2021), growth of kale was demonstrated to vary under the same temperatures with different levels of ambient carbon dioxide concentrations and relative humidity. In this experiment, the optimal conditions for kale growth were: 20-23 ºC, 85% humidity, and 700-1000ppm of CO_2 (Chowdhury, 2021). Therefore, the optimal values of the discussed variables need to be considered in conjunction with one another and presented as a recipe.

Due to the effects of multiple variables have on a crop at a given time, research is currently being done to develop crop growth models considering the interplays of multiple variables. Crop growth models provide data on what a plant requires physiologically at different growth stages under different environmental conditions (Zhang, 2025). These models when paired with climate models, may be able to predict what kinds of resources a plant requires on a daily basis to minimize resource waste (Zhang, 2025).

2.2 Energy Consumption

There are various factors that contribute to the overall energy consumption of a vertical farm, including lighting; control and data collection; irrigation; and HVAC. This review focused on how calculating the energy consumption of these factors and how different technologies and operational strategies can change energy consumption.

2.2.1 Lighting

A major component of energy consumption for enclosed vertical farms is lighting. A 2021 census produced by Agritecture showed that energy consumption rates for lighting varied and could account to 55% of total energy usage for enclosed vertical farms (Agritecture, 2021). Exact consumption and percentage however vary depending on the crops grown, the type of light selected, and the layout plan. When selecting lighting devices, the factors to be considered include the efficacy, power consumption, spacing, and time.

Efficacy

When considering efficiency of lighting devices, commonly the optical output is divided by the electrical power input and converted to a percentage (Kusuma, 2020). The indicator that is more relevant to overall consumption rates for vertical farms however is efficacy. Efficacy is a measure of µmol of PAR light (photons) produced by a lighting device per joule of electrical energy consumed, expressed as µmol/J (Kusuma, 2020). The average theoretical maximum (assuming 100% of all electrical energy is converted into µmol of PAR light) is 5.1 µmol/J (Kusuma, 2020). If the efficacy of a lighting device is not 100%, the remaining amount of energy becomes waste heat. An interesting point to note is that blue light has a lower theoretical maximum efficacy (3.76 µmol/J) than red light (5.52 µmol/J) because blue light has a shorter wavelength than red light, which requires more electrical energy to produce photons (Kusuma, 2020). However, as discussed previously, blue light has many benefits to plant growth, although it may be a higher energy consumption light source.

Spacing and Power Consumption

Spacing between light fixtures and crop canopies, as well as between light fixtures must be considered to ensure the lighting level and uniformity. For example, the low-power L28 series PPFD map shown in (Fig. 2) was for light fixture spaced 152 mm from the plant canopy, whereas the high-power Bx120c2 series lights (Fig. 3) were spaced 254 mm from the canopy. The short spacing could be an unrealistic selection as studies have found that providing light with only 200 mm from the canopy produced crops with deformities and were not marketable (Voutsinos, 2021). Spacing affects the number of light fixtures required to provide the desirable lighting level, and the number of light fixtures plays a key role in power consumption. For instance, to achieve a 300 µmol/m^2 PPFD for a 5.8 m^2 area both the L28 AP673L light series (Fig.2), or the Bx120c2 series provided by Valoya could work (Fig. 3) The L28 series requires 16 lights, each 27W for a total power consumption of 432 watts. The Bx120c2 series requires 8 lights, each 135W for a total of 1,080W.

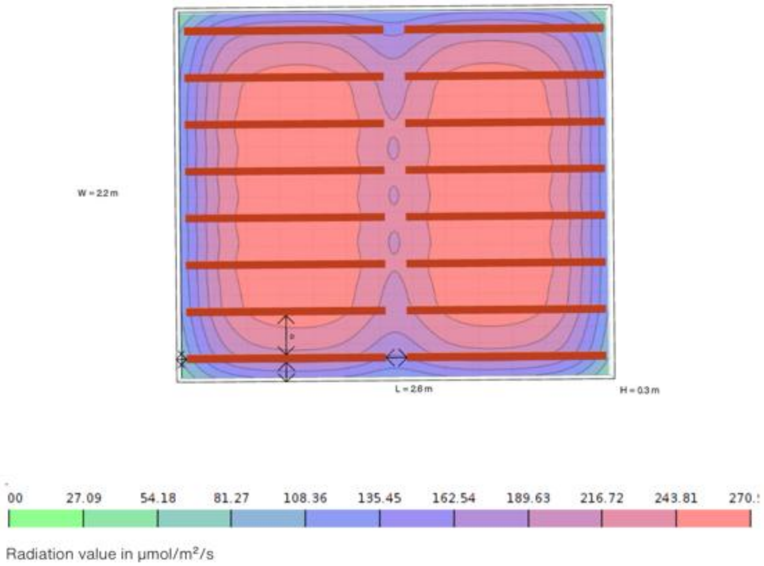


Figure 2 *PPFD Map for L28 AP673L Light Series (Kendrick, 2023)*

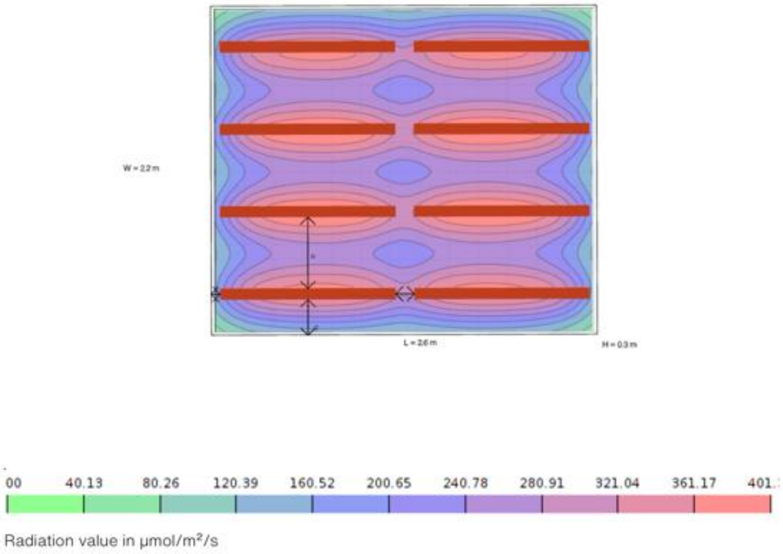


Figure 3 *PPFD Map for Bx120c2 Light Series (Kendrick, 2023)*

Lighting period

The last factor that influences energy consumption of lighting is the length of time that lights are on for. This is determined by the photoperiod requirement of the plant, at the intensity supplied.

As discussed, there are multiple factors that influence the energy consumption of lighting, and there is currently several research conducted to find ways to reduce energy consumption of lighting. An example is using dynamic control to adjust light intensity and duration based on electricity prices and by detecting physiological responses in plants (Morrison, 2024). This type of operation strategy however is contingent on the control mechanism within the vertical farming space.

2.2.2 Nutrient Delivery System

Past studies have reported that irrigation and nutrient delivery requires a low percentage of total energy used in vertical farms. One report by W. Cal et. all indicated irrigation accounts for approximately 4% of usage (2024). Energy consumption for irrigation involves running pumps and dosers in the nutrient delivery system. This is a small contributor to energy consumption as no credible sources were found stating the percentage these systems attribute to in the overall energy footprint of farms. A standard nutrient delivery system consists of a reservoir that mixes nutrients and water in preparation for delivery. Energy consumption includes pumps to deliver the solution, and a controller/doser to regulate the amount of nutrients (Anon, 2024). Energy consumption however varies depending on the type of system selected, as nutrient delivery systems can be simple (relying on gravity for distribution), or more complex (consisting of sensors, pumps and timers) (Anon, 2024).

Different methods of indoor growing require different amount of energy to operate. For deep water culture systems (DWC) and nutrient film technique set-ups (NFT), air pumps and submersible pumps run continuously, while Ebb & Flow systems are becoming popular from an energy consumption point of view as a timer can be set to run nutrient rich water at intervals, and thus saving energy (Nelson, 2025).

2.2.3 HVAC

After lighting, the next highest contributor of energy consumption in vertical farms is HVAC (heating, ventilation and air conditioning) (Arcasi, 2023). Proper HVAC equipment is required to ensure the crops have adequate temperature and humidity conditions (Arcasi, 2023). Ideal temperature and humidity conditions differentiate based on the crop produced. For example, ideal growing conditions of lettuce are approximately 18°C and 65% RH creating an optimal VPD value

of 0.69kPa (Amitrano, 2021). Maintaining the optimal conditions in vertical farming facilities may require heating in the winter, cooling in summer, and ventilation in all seasons to remove moisture. All these operations are energy intensive.

Heating and Cooling Loads

The factors that impact heating loads include building envelope construction, lighting load, plant density and location (Ahamed, 2023). Typically increased thermal insulation within the building envelope will decrease heating loads. A study of Harbrick and Albright (2016) reported 19 – 23 kWh per kg of lettuce grown in an enclosed structure, in comparison to 7-8 kWh per kg of lettuce grown in other cities worldwide (Ahamed, 2023).

Location is a critical factor in determining heating and cooling loads as ambient temperatures influence heat loss/gain in a vertical farming facility, including solar radiation.

Some studies have suggested that location has a negligible effect on heating, as lighting systems may generate sufficient heat to compensate heat losses from the buildings (Graamans, 2020). A modelling study for vertical farms in Sweden (-30°C ambient temperatures) reported negligible calculated heating loads for lettuce (Grammans, 2020). On the other hand, heat generated by LEDs and other internal sources may impact cooling loads of a vertical farm. Cooling loads been reported by multiple studies to consist of 10 – 45% of total energy consumption (Ahamed, 2023).

Plant density impacts the heating and cooling loads in vertical farming facilities due to plant transpiration and evaporation (Graamans, 2017). Graamans (2017) modelled the behaviour of plants and their transpiration rates while considering the amount of LED lighting supplied to the canopy to quantify it's effects on the energy balance of a vertical farm. They concluded that the higher density of plant production, the more sensible and latent heat conversion occurs.

An air economizer provides cooling to a vertical farm using cool outdoor air instead of a condenser and cooling coil system. The only energy required in this process is the power to run the fan, which is significantly less than what a condenser and cooling coil system requires. A study conducted on energy savings for vertical farms found that using an air-side economizer reduced cooling energy consumption by 40-69% depending on geographic location (Eaton, 2022).

Many technologies are available on the market to address energy consumption challenges of vertical farms, with a focus on reducing HVAC loads. Solar walls can be used to reduce heating requirements in greenhouses, air temperature can be lowered using root zone heating, and continuous improvements to LED lights can reduce electricity loads (Vatistas, 2022).

Dehumidification

As plants transpire, the humidity of the interior space begins to increase, thus requiring dehumidification for humidity control. The dehumidification capacity and energy consumption is dictated by the plant transpiration rate, which depends on: the amount of radiation (lighting) absorbed by a crop, the leaf area, the difference between air and leaf temperature, stomatal resistance, and aerodynamic resistance of the crop canopy (Graamans, 2017). Humidity levels can be controlled in a variety of ways, such as ventilation, heat pumps, heat recovery ventilators and even using hygroscopic materials to absorb moisture (Ahmad, 2023). Both the method of humidity control and the evapo-transpiration rate of the crop affects the overall energy consumption of dehumidification.

Airflow

Airflow at the plant canopy is essential for healthy growth. Providing adequate, consistent airflow however in vertical farms can be a challenge because growing tables and shelving units can create many microclimates (Ahamed, 2023). Microclimates can arise when stratification occurs around the plant canopy. To avoid the creation of stratification, multiple methods can be used to improve airflow at the plant canopy. Some studies have found that placing axial fans (a common solution) in front of the canopy improves airflow but may still result in a temperature gradient not optimal for plant growth (Goto 2012). Another solution that researchers have found to work better is installing vertical airflow systems with perforated tubes (Shibuya et al., 2006).

When considering the energy usage of interior airflow, the method used for delivery, the power of the fan, and duration of operation all need to be considered.

2.2.4 Control Devices

Controls are an essential element for successful vertical farming operations. Control methods can range from simple stand-alone options such as mechanical timers and dimmers to integrated systems such as climate controls, irrigation controls, and dynamic controls.

Different control options may result in different amounts of energy consumption. For example, using an Arduino controller and sensors to control temperature, pH and EC of nutrient solution may optimize nutrient usage, while reducing electrical consumption of irrigation system (Michael, 2021). More advanced controls used in past studies include integrating sensors for ambient temperature, water temperature, humidity, pH, and light to control and optimize HVAC, lighting and irrigation (Chuah, 2018). A control option such as this, is an integrated climate control method where nutrients, light and temperature changes are done in conjunction with the plants needs. When integrated energy-efficient climate control technologies are implemented in vertical farms, optimal growth conditions can be achieved, and energy is saved (Marcelis et. al, 2024). Recent advancements in controls also include integrating artificial intelligence and machine learning algorithms to control environmental processes based on plant conditions (Anubhove, 2020).

2.2.5 Overall Energy consumption

Several studies on the overall energy usage of vertical farms have been reported in the last two years. In general, heating consumption can account for up to 500 kWh/m^{2}yr and LEDs can require up to 12,000 kWh/m^{2}yr (Vatistas, 2022) depending on the size of the facility. A recent literature review conducted by Miserocchi et. al (2024) summarized the results from 16 different studies on energy usage of vertical farms (with a focus on lettuce production) to benchmark energy usage of various mechanical systems in VF. The findings indicated that most studies reported 10-18 kWh/kg of lettuce grown, or between 850 – 1150 kWh/m^{2}yr. They suggested that the benchmark for energy requirement of LEDs was 2.3 kWh/kg and HVAC between 0.5 kWh/kg to 2.5 kWh/kg (Miserocchi, 2024).

2.3 Energy Modelling

The most critical challenge in vertical farming for localized food production is high energy demand to operate lights (LEDs), HVAC and irrigation (Weidner, 2022). The amount of research on energy consumption and modelling of vertical farms has significantly increased in the last three years. Some of the key studies are highlighted below.

Weidner et.al. (2022) conducted a study of using energy models to optimize vertical farming operations. In their study a yield-energy model was used to predict growth rates and energy consumption for greenhouses and enclosed vertical farms in 10 different geographic locations. The findings indicated that depending on the geographic location, greenhouses were between 45 – 94% more energy efficient than vertical farms for the geographic locations considered in the study (Weidner, 2022). Canada was not one of the geographic locations included in this study.

Another study by Nicholas Engler (2021) was focused on energy optimization analysis of net zero energy greenhouses. This study was a literature review that assessed energy consumption rates of greenhouses primarily located in the United States and did not include enclosed vertical farms. This review concluded that due to lighting requirements, vertical farms require twice as much energy as greenhouses (Engler, 2021). However, improvements to building envelope, HVAC & lighting efficiency can reduce energy consumption rates by 75% (Engler, 2021).

Talbot et.al (2024) developed a high density CEA model to predict energy consumption and crop growth rates under various temperature, humidity, and lighting conditions. This model was created in TRNSYS, which a software tool for modeling and simulating thermal and electrical energy systems. The percentages of energy usage for lighting, cooling, dehumidification and heating were predicted under a combination of 180 conditions. The findings indicated that crop yield was the highest under 24°C air temperature providing the best specific energy load (Talbot, 2024).

Although there has been a recent uptake in research on energy modelling of VF, one of the limitations it that most studies that combine energy consumption with crop performance are only simulated scenarios without limited experimental validation. For example, In the study reported by Miserocchi et.al (2024) out of the 16 cases reviewed, only three of them involved measurement scenarios. Furthermore, few studies considered the types of commercially available indoor growing systems — which would impact growth rates depending on the type of method used (e.g., hydroponics vs. aeroponics systems).

The majority of past studies assumed ideal constant plant conditions — which is typically unrealistic especially in small start-up vertical farm operations. Therefore, integrating the influence of varying degrees of control systems on crop production and energy consumption for given types of crops has not been explored.

3.0 Objectives

The purpose of this thesis project was to analyze and model energy consumptions in vertical farming in cold climate conditions. The specific objectives were:

1) To conduct experiments in a pilot vertical farming facility to measure and analyze energy consumptions by the key processes in vertical farming, including lighting, HVAC, nutrient delivery, and monitor and control systems.
2) To specifically assess the energy consumption and feasibility of operating a Smart Vertical Farm (SVF) in a cold northern climate.
3) To develop and validate a model for predicting energy consumption in vertical farming designs.

4.0 Materials and Methods

The modelling was focused northern climates as well and includes parameters affecting both the plant and root environments for crop growth. Growing lettuces was used as a placeholder in model development.

4.1 Energy Model Development

Energy consumption was calculated based on the type of heating, cooling and ventilation system chosen as well as the influences of control. The building envelope and geographic location were also taken into consideration for affects of ambient temperature and humidity on HVAC performance.

The procedure of energy consumption calculations is illustrated in the flow chart below. The flow chart represents the sequence of operations the model undergoes to calculate total energy usage based on user inputs, (which are explained in the following sections). These inputs are also processed into relevant sub-modules which will calculate energy consumption for major energy consuming systems of the farm (such as HVAC, lighting and irrigation). Energy consumed by HVAC is calculated last in the model because criteria regarding consumption of lighting (such as heat gain emitted by LEDs), will affect the total HVAC load. Equations used in the model are within different text blocks, as demonstrated in Fig.4.

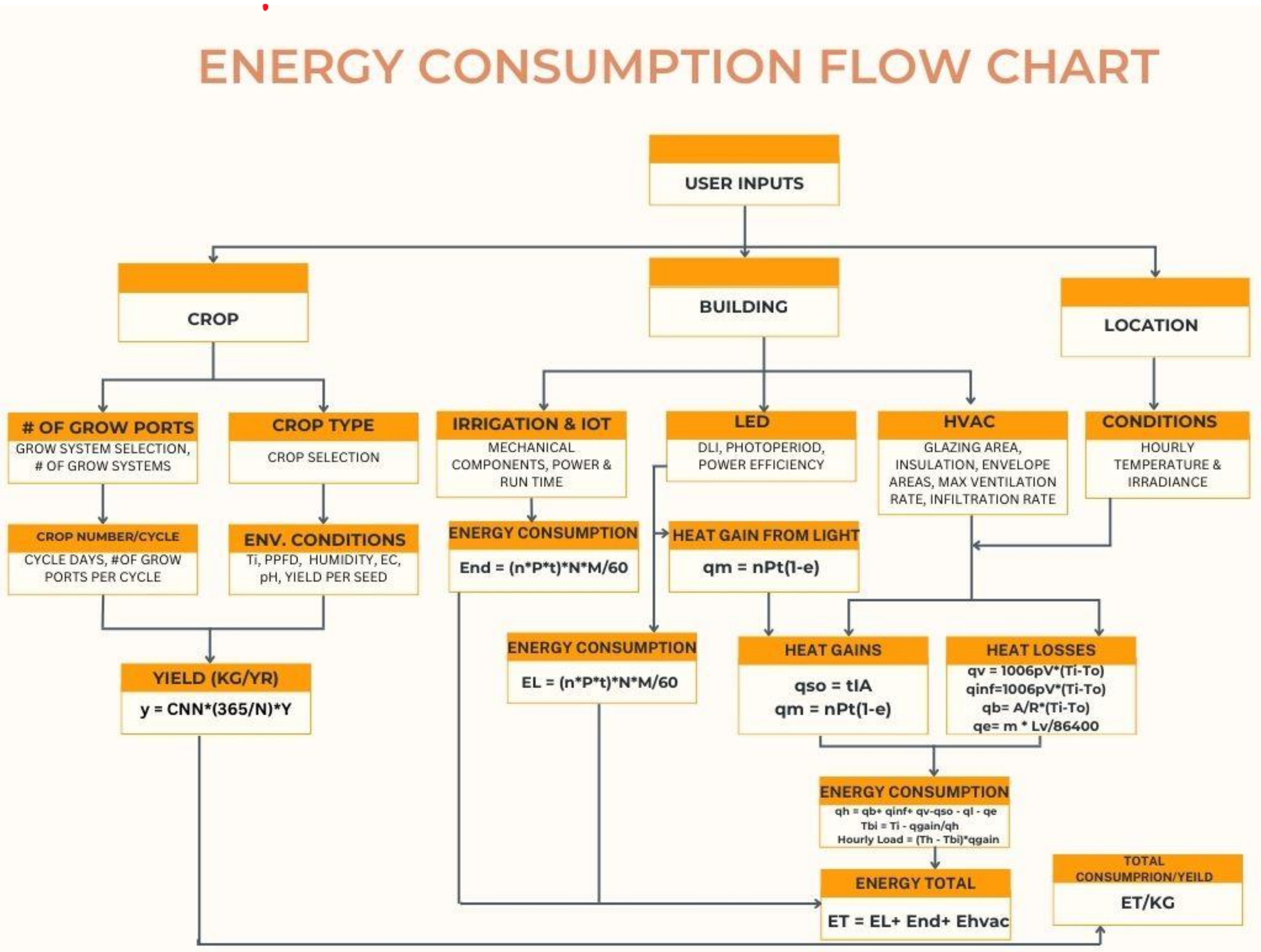


Figure 4 *Energy Model Flowchart*

The model was coded in MATLAB and was designed to be industry acceptable and user-friendly so it can be easily implemented commercially. As such, many of the input parameters are designed to be user-inputs to accommodate large variations in vertical farming facility design.

4.1.1 Theories and Individual Model Components

Crop Variety and Yield

The first section of the model was used for predicting yield based on available growing space, and required environmental conditions for the crop variety. Available growing space is the total number of growing ports in the grow space, which was calculated based on the number of ports per individual growing system used, and the total number of growing systems. Yearly yield was calculated using equation 1, which takes into account cycle days of the crop variety selected, the total number of grow ports, and the average yield per individual grow port.

$$Y = CNN * \left(\frac{365}{N}\right) * y \qquad (3)$$

Where
Y = Total yearly production (kg)
CNN = Total number of grow ports
N = Total number of days in one grow cycle
y = Average yield per individual grow port (kg)

The average yield per individual grow port was based on recorded data from the experiment conducted in this study. The climate conditions used during this procedure that correlated to this yield are explained further in the user experience section.

Energy Consumption – Lighting

The electrical energy consumed by lights were calculated based on the power consumption of each individual light, the number of lights, and the duration the lights were on for. Two electrical loads were calculated to account for the nursery phase and the vegetative phase of crops. The equation used however was the same and is listed below (equation 4).

$$E_L = n * P * T * N * M \qquad (4)$$

Where:
E_L = yearly energy use (kWh)
n = number of lights
T = photoperiod (hours/day),
P = rated power per light (kW)
N = Total number of days in one grow cycle
M = Total number of grow cycles in a year

It should be noted that the energy consumption for the vegetative and the nursery phase of plants were calculated separately and then added together as the total energy consumption of lighting:

$$E_{tot} = E_{L1} + E_{L2} \qquad (5)$$

Where:
E_{tot} = total energy used for lights (kWh)
E_{L1} = electricity used for lights during nursery phase (kWh)
E_{L2} = electricity used for lights during vegetative phase (kWh)

Energy Consumption – Irrigation

The electrical load for irrigation was calculated based on the power requirements and run time of any aeration, fertigation, and water delivery pumps as follows:

$$E_a = \Sigma(n_a * P_a * T_a) * N * M/60 \tag{6}$$

$$E_{nd} = \Sigma(n_w * P_w * T_w) * N * M/60 \tag{7}$$

Where:
E_a = total yearly energy consumption for aeration pumps (kWh)
E_{nd} = total yearly energy consumption for nutrient delivery pumps (kWh)
n_s= number of air pumps
n_w = number of water pumps
P_a = power consumption for air pumps (W)
P_w = power consumption for water pumps (W)
T_a = run time of air pumps per day (minutes)
T_w = run time of water pumps per day (minutes)

Energy consumption for nutrient delivery and aeration were then added together to get total irrigation energy consumption using equation 8.

$$E_{it} = E_a + E_{nd} \tag{8}$$

Eit = total yearly energy consumption for irrigation (kWh)

Energy Consumption – Data & Controls

The electrical load for data and controls were calculated by the summation of the power draws of all individual IoT sensors and controls used in a farm. The electrical load of individual components were calculated using equation 9. The run time in this scenario was assumed to be 24/7. The total consumption used by data collection and controls was calculated using equation 10.

$$E_{dat} = (n_i * P_i) \tag{9}$$

$$E_{dct} = \Sigma E_{dat} \tag{10}$$

Where:
E_{dat} = total yearly electrical load for IoT device/control (kWh)
E_{dct} = total yearly electrical load for data and controls (kWh)
n_i = number of IoT device/control
P_i = power draw of component

Energy Consumption - HVAC

The HVAC load was first calculated based on a heat balance equation that is specific to vertical farms. A general heat balance equation can be written as:

$$q_h + q_{so} + q_l \pm \ q_e = q_b + q_{inf} + q_v \tag{11}$$

Where:
q_h = overall heat flux term (W)
q_{so} = sensible heat gain from solar radiation (W/K)
q_l = heat gain from lights (W)
q_e = heat loss from plants evapotranspiration (W)
q_b = heat loss from envelope (W/K)
q_{inf} = heat loss from infiltration (W/K)
q_v= heat loss from ventilation (W/K)

In this heat balance equation, the heat gains are on the left hand side, and the heat losses are on the right hand side. The term q_h represents the overall heat gain or loss in the farm, and was used to calculate both the heating and cooling loads: a positive q_h value is the heating load and negative is the cooling load. Other terms in the equation are discussed as follow.

Heat Gain Due to Solar Radiation

Heat gain from solar radiation was calculated using the sol-air temperature method as follows:

$$q_{so} = Uc * (T_i - T_{sol}) * A \tag{12}$$

$$T_{sol} = T_h + \frac{(\alpha * Iso)}{ho} \tag{13}$$

Where
q_{so} = Heat gain from solar radiation (W)
Uc = Thermal transmittance of the building envelope (W/m^2K)
T_i = Interior temperature (°C)
T_h = Ambient temperature (°C)

A = Area of exterior walls (m^2)
α = Solar absorptivity of the surface (dimensionless)
I_{so} = Total solar irradiance (W/m^2)
h_o = Heat transfer coefficient for radiation and convection at the outer surface (W/m^{2}K)

Heat Gain due to Lights

Although light emitting diodes (LEDs) are typically viewed as an energy efficient light source, these lights still give off a considerable amount of heat during operation, which was calculated as follows:

$$q_l = n * P_{lt} * f \tag{14}$$

$$f = (1 - ee1/5.1) \tag{15}$$

Where:
q_l = Heat gain from lights (W)
n = Number of lights
P_{lt} = Power consumption of lights (W)
f = Percentage of power converted into heat (%)
ee1 = efficacy of lights (µmol/J)

The percentage of power converted into heat can be calculated based on the efficacy of the lights, which is a unit listed on a lights' mechanical specification sheet. The efficacy value determines the amount of µmol of light that can be converted per joule of electrical energy. The theoretical maximum of electrical energy that can be converted into PAR light is 5.1 µmol/J (Kusuma, 2020). Therefore, the amount of electricity lost to waste heat can be calculated by dividing by the theoretical maximum (equation 15) and subtracting that value from 1.

Plant Evapotranspiration

The sensible heat loss from plants evapotranspiration rates were calculated using the Penman-Monteith method and the latent heat of vaporization coefficient. The Penman-Monteith method estimates the amount of evapotranspiration that occurs at a plant canopy considering environmental factors such as crop coverage, temperature, humidity, wind speed, solar radiation, and other factors (Allen, et. Al, 1998).

The first step in the Penman-Monteith method is to solve for the saturation vapor pressure, Es, which is typically from the minimum or maximum air temperature of the space. As temperature is to be controlled for vertical farms, the design temperature was used here (Allen et al. 1998):

$$E_s = 0.6108 * \exp\left(\frac{17.27 * Ti}{Ti + 237.3}\right) \tag{16}$$

Where:
Es = Saturation vapor pressure of the environment (kPa)
Ti = Air temperature (°C)

The average vapor pressure is then calculated based on the temperature and relative humidity ranges as follows:

$$E_a = \frac{Es*\left(\frac{Rhmax}{100}\right) + Es*\left(\frac{Rhmin}{100}\right)}{2} \tag{17}$$

Where:Ea = Actual vapor pressure (kPa)
Es = Saturation vapor pressure (kPa)
Rhmax = Maximum relative humidity
Rhmin = Minimum relative humidity

Once the average and saturated vapor pressures were known, the evapotranspiration rate was calculated (Allen et al. 1998):

$$E_{To} = \left(\frac{0.408*\delta*(Rad - G) + \varphi*\left(\frac{900}{ti+273}\right)*u2*(es - ea)}{\delta + \left(\varphi*(1 + 0.34*u2)\right)}\right) \tag{18}$$

Where:
ETo = Reference evapotranspiration rate (mm/day)
δ = Slope vapor pressure curve (kPa/°C)
Rad = Net radiation at the crop surface (MJ/m^{2}d)
G = Soil heat flux density (MJ/m^{2}d)
φ = Psychometric constant (kPa/°C)
Ti = Design temperature (°C)
u2 = Wind speed at 2m surface height (m/s)
Es = Saturation vapor pressure (kPa)
Ea = Actual vapor pressure (kPa)

The variable ETo is the reference evapotranspiration based on the controlled environment conditions of the space. The variable ETc is the adjusted evapotranspiration rate which is based on the type of crop that is growing in the controlled environment. The soil heat flux density value (G) was set to zero. Outdoors, the exposed surface of soil will contribute to the evapotranspiration rate of the plant canopy. Indoors however, soil surface exposure is negligible, if not zero altogether (for full hydroponic set-ups).

$$E_{Tc} =(E_{To} * K_{cb}) \tag{19}$$

The Kcb value used in this model was 0.90 which is the coefficient used for lettuce at each of its growth stage (UN, 1998).

The actual moisture production rate of plants were calculated from the adjusted evapotranspiration rate by consider the cropped area, which is the growing area of the indoor unit multiplied by the number of units in the space ad follows (Allen et.al, 1998):

$$\dot{M} = \left(\frac{Agro*Etc*0.001}{86400}\right) \tag{20}$$

Where:
$\dot{M}$= moisture production rate (mm3/day)
Agro = crop canopy area (m2)

The sensible heat loss due to evapotranspiration was predicted from the moisture production:

$$Q_e = \dot{M} * \frac{\mathrm{Lv}}{86400} \tag{21}$$

Where:

Lv= latent heat of vaporization (2259.36 J/g)

Heat Losses through Building Envelope

Heat losses for vertical farms were calculated based on conduction losses through the building envelope (equation 22), through infiltration (equation 23), and through convection (equation 24). Envelope losses are calculated based on the thermal resistance of the wall assembly, the area of the exterior walls and the difference between the ambient and indoor design temperature.

$$q_b = \Delta \mathrm{t}(\frac{\mathrm{A}}{\mathrm{R}}) \tag{22}$$

Where:
qb = Heat loss through the building envelope (W)
Δt = Difference between ambient and indoor temperature (C)
A = Area of exterior building surface (walls, ceilings, etc) (m^2)
R = Thermal resistance of wall assembly (W/m^2K)

Heat loses due to infiltration were calculated based on the rate of air infiltrating the building enclosure. In the model, the user rates the leakage of the building, which is associated to an air change per hour value. The options provided to the user were "not leaky" was assigned an ACH value of 0.5, "average" a value of 2, and "leaky" a value of 5.

$$q_{inf} = 1006\rho\dot{V}_{inf} * (T_i - T_o) \tag{23}$$

Where:
q_{inf} = Heat loss due to air leakage. (J, W/s)
Vinf = Infiltration volume through the building (m^3/s)
ρ = Air density (1.225 kg/m^3)
R = Thermal resistance of wall assembly (W/m^2K)
Note: 1006 is the specific heat capacity of air in (J/kg°C)

Heat loss due to ventilation was determined in the same fashion as infiltration.

$$q_v = 1006\rho\dot{V}_v * (T_i - T_o) \tag{24}$$

Where:
q_v = Heat loss due to ventilation (W/s, J)
$\dot{V}_v$ = Ventilation volume (m3/s)
p = Density (1.225 kg/m3)
T_i = Indoor design temperature (°C)
T_o = Ambient temperature (°C)
Note: 1006 is the specific heat capacity of air in (J/kg°C)

To calculate the ventilation volume for humidity control, equation 25 is used.

$$V = \frac{m_p}{p_{air}} * (W_i - W_o) \tag{25}$$

Where:
V= Volume of ventilation air (m^3/s)
mp = Moisture production rate (m^3/s)
p_{air} = Density of air (1.225 kg/m^3)
W_i = Indoor design humidity ratio (kg of moisture/kg of dry air)
W_o = Outdoor humidity ratio (kg of moisture/kg of dry air)

Energy Consumption - Variable Base Degree Method

There are several methods to calculate HVAC loads using the heat balance equation. The method chosen for this study was the Variable Base Degree method (Christensen, 1983). The variable base degree method calculates a separate balance temperature every hour based on interior and exterior heat gains and losses to indicate if the space requires heating or cooling for that hour. To apply the variable base degree method, a new balance design temperature was calculated for every hour, using equation 28.

$$T_{bi} = T_i - (\frac{q_{gain}}{qh * \Delta t}) \tag{26}$$

Where:
Tbi = Design balance temperature for when heating or cooling is required (°C)
Ti = Design temperature (°C)
qgain = Hourly interior heat gain of the space
qh = Hourly heat flux multiplied by delta T.

Once the balance temperature was calculated, the hourly heating/cooling load, based on the design temperature calculated in equation 27.

$$Hourly\ Load = (T_h - T_{bi}) * q_h \tag{27}$$

Where:
Th = Ambient temperature at 2m from the surface (°C)
Tbi = Hourly interior design balance temperature (°C)
qh = Hourly heat flux term.

Climate data from the NASA Power Data Access Viewer (DAV), was used for the surrounding Winnipeg area. One year of climate data was pulled from March 1st 2023, to March 1st 2024. The variables that were used includes total solar irradiance, and ambient temperature 2m from the surface.

To calculate a new balance temperature for every hour, a for loop was created in the model to read solar irradiance and ambient temperature every hour from the DAV database.

For every hour a new qsb term was calculated to properly account for affects of solar irradiance. Additionally, two qgain factors were calculated in order to account for two different conditions of the farm; one where the LEDs were on, and the second where the LEDs were off. These factors (represented as qgain1 and qgain2), were then used to calculate two new balance design temperatures at which heating or cooling were required. The hour of the day would determine which balance design temperature would be used, in order to match the photoperiod cycles of the lights.

The balance design temperature was then compared to the ambient temperature. If the balance design temperature was higher than the ambient, a loop was created to add the load for that hour to the cooling load. If the balance design temperature was lower than the ambient, a loop was created to add the load for that hour to the heating load. A delta t term was calculated and multiplied the overall heat flux term of the space (qh), which was then added to the HVAC load for that month. Yearly and monthly energy loads were summarized for each category of energy consumption produced by the model. The monthly loads for HVAC were able to be calculated as the data supplied by the DAV had a placeholder for the month in which the data was collected. Therefore, an if loop was created within the for loop which added the hourly heat load to the prospective month the data was collected for.

The output of the model was a table that summarizes the yearly and monthly energy loads for lighting, irrigation, data and controls, heating, cooling and indoor air flow. This table was then compared to measured results for energy consumption of the experimental farm for an accuracy assessment.

Energy Consumption – Air Circulation Fans

Energy consumption by fans for indoor air circulation is calculated independently of heating and cooling loads.

$$IndoorairNrg = fanc * 24 * N * M \tag{28}$$

Where:
IndoorairNrg= Energy consumed by indoor fans (kWh)
fanc = Power draw of indoor fans (W)
N = Number of days in a grow cycle
M = Number of grow cycles in a year

4.1.2 Energy Calculations Summary

Energy consumption loads were calculated individually for lighting, irrigation, data control, heating, cooling, dehumidification and indoor air circulation. The table below is a summary of the parameters used for calculations as well as the methods and equations associated with each of those calculations.

Table 1 *Summary of Equations and User Prompts Used in Model*

Energy Load Factor	User Prompts	Equations
Lighting	No. of Lights Rated power Consumption Photoperiod	$E = n * P * T * 365 \quad (3)$ $Etot = EL1 + EL2 \quad (4)$
Irrigation	No. Of air pumps No. Of water pumps Rated Power Consumption Daily Run Time	$Ea = \Sigma(n * P * T) * 365\ (5)$ $End = \Sigma(n * P * T) * 365\ (6)$ $Eit = Ea + End\ \ (7)$
Data Collection	Power draw of various components	$Edatan = \ (n * P * T) * 365\ (8)$ $Edct = \Sigma Edatan\ (9)$
Heat Gains	Light efficacy Min/max temperature Min/max humidity	$efficency = \frac{ee1}{5.1}\ \ (10)$ $qlin = \ (n * P * (1 - efficency)\ (11)$ $qliT = qlin + qliv \quad (12)$ $qsb = Uc * (ti - Tsol) * A\ \ (13)$ $Tsol = Th + \frac{(Alpha * Iso)}{ho}\ (14)$ $Es = 0.6108 * \exp\left(\frac{17.27 * ti}{ti + 237.3}\right)\ \ (15)$ $Ea = \frac{es * \left(\frac{Rhmax}{100}\right) + es * \left(\frac{Rhmin}{100}\right)}{2}\ (16)$

Energy Load Factor	User Prompts	Equations
		$ETo = \left(\frac{0.408 * delta * (Rad - G) + psy * \left(\frac{900}{ti + 273}\right) * u2 * (es - ea)}{Delta + \left(psy * (1 + 0.34 * u2)\right)}\right)$ (17) $ETc = (ETo * Kcb)$ (18) $Mprod = \left(\frac{Agro * Etc * 0.001}{86400}\right)$ (19) $Qglw = \mathrm{Mprod} * \frac{\mathrm{Lv}}{86400}$ (20)
Heat Losses	Area of building envelope Thermal insulation (R) Leakiness of Building	$q_b = kA * \left(\frac{\Delta t}{\Delta x}\right) = \Delta \mathrm{t}\left(\frac{\mathrm{A}}{\mathrm{R}}\right)$ (21) $q_{inf} = 1006p\dot{V}_{inf} * (t_i - t_o)$ (22) $q_v = 1006p\dot{V}(t_i - t_o)$ (23) $V = \frac{q_s + q_m + q_{so} - \left(\Sigma\frac{A}{R} * \Delta t\right)}{1006p * \Delta t}$ (24) $V = \frac{m_p}{p_{air}} * (Wi - Wo)$ (25)
Heating & Cooling Loads	Rated power consumption of: AC unit Boiler of circulation fan	$qh = qb + qinf + qv - qso - qe - qm$ (26) $Tbi1 = Ti - \frac{qgain1}{qh * delta\ T}$ (27) $Tbi2 = Ti - \frac{qgain2}{qh}$ (28) $Hourly\ Load = Th - Tb * qh$ (29) $IndoorairNrg = fanc * 24 * 365$ (30)

4.1.3 User Interface of Energy Model

User Prompts – Crop Variety & Yield

The energy model prompts the user for a variety of selections in order to fill in the variables for all of the equations discussed. The first set of prompts starts with allowing the user to select which indoor growing system will be used in their farm (Fig. 5). The model currently has built-in information on three commercial growing systems – Harvest Today Wall, Argotonomy Tower, and ZipGrow Tower.

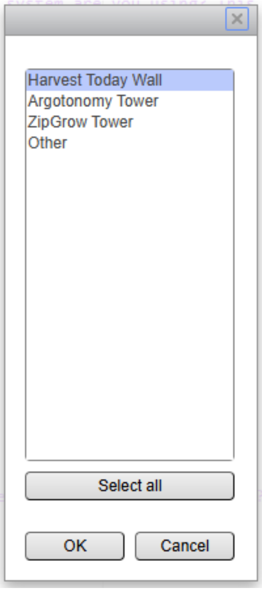


Figure 5 *User Prompts for Indoor Growing System Selection*

Once a growing systems is selected, the next set of prompts requires the user to enter information on the selected growing system, including the grow systems dimensions, the number of ports, and the total number of systems.

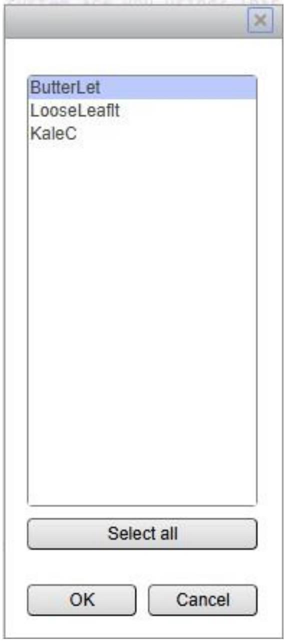


Figure 6 *User Prompts for Crop Variety Selection*

The next input screen prompts the user to select which crop to grow (Fig 6). Only three options are available; butter crunch lettuce, loose leaf lettuce, and kale. Based on the selected crop, the environmental temperature, humidity, VPD, EC and pH are automatically filled based on a crop database table created for this model (Table 2). The crop database table was created based on experiments ran in the urban farm that translated to an average yield used to calculate production. The table was designed this way to also provide users data on yield only under set average conditions shown. Manipulating one or more of these factors may increase the yield, and speed up growth rate.

Table 2. *Ideal Grow Conditions for Various Crops (cite sources/references of this information)*

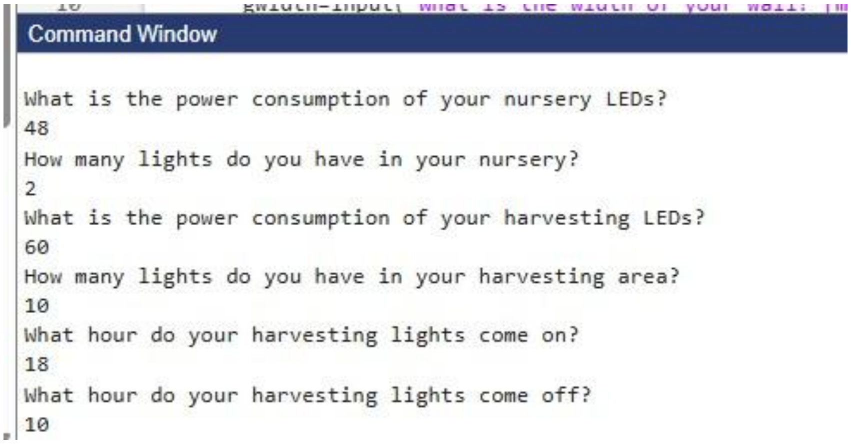
Crop	**Temp (°C)**	**Humidity (%)**	**VPD (kPa)**	**Wind speed (m/s)**	**EC (uS/m)**	**pH**	**DLI (mol/m^{2}d)**	**CO2 (ppm)**	**Cycle Days**	**Yield (g/port)**
Butter Crunch Lettuce	22	65	0.82	1.5	1.5	5.5	14.5	600	40	45

Crop	Temp (°C)	Humidity (%)	VPD (kPa)	Wind speed (m/s)	EC (uS/m)	pH	DLI (mol/m^{2}d)	CO2 (ppm)	Cycle Days	Yield (g/port)
Loose Leaf Lettuce	22	65	0.82	1.5	1.5	5.5	14.5	600	40	80
Kale	22	65	0.82	1.5	1.5	5.5	14.5	600	40	70

Parameters that were not considered in this table include; oxygen content of solution, water temperature, photoperiod and PPFD. Photoperiod and PPFD were excluded from the database table as the more important governing variable is DLI. Photoperiod and PPFD are also dependent on the grow light selected, which are inputs required by the user discussed in the following section. Oxygen content and water temperature were also not included as they were deemed out of scope for this research project.

User Prompts – Electrical Load for Lights

The next set of input screens (Fig. 7) allows the user to enter the details of lighting system, including the rated power consumption (in Watts), and the run time (in hours). These inputs will be used to calculate energy consumption of the lighting system. There is a separate input required for lights used in the nursery station and lights used in the main cultivation area.

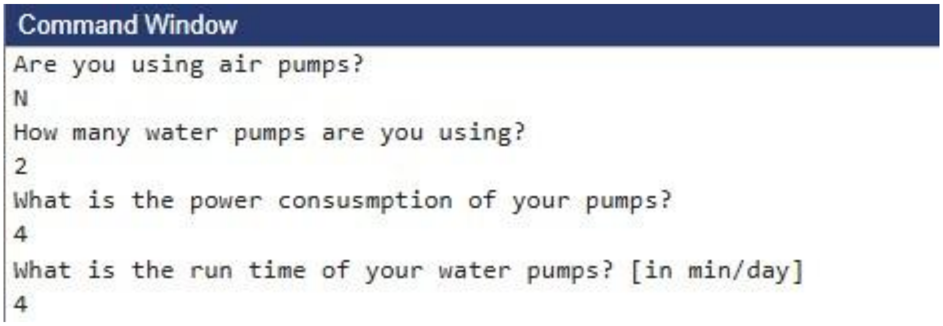


```
What is the power consumption of your nursery LEDs?
48
How many lights do you have in your nursery?
2
What is the power consumption of your harvesting LEDs?
60
How many lights do you have in your harvesting area?
10
What hour do your harvesting lights come on?
18
What hour do your harvesting lights come off?
10
```

Figure 7 *User Prompts for Lighting Loads*

User Prompts – Electrical Load for Irrigation

The next section of the model prompts the user for number of air/water pumps, and run time of each piece of equipment (Figure 8). Air pumps are an additional piece of equipment not always included in a farm facility, which is why a Yes or No prompt was asked first.



```
Are you using air pumps?
N
How many water pumps are you using?
2
What is the power consusmption of your pumps?
4
What is the run time of your water pumps? [in min/day]
4
```

Figure 8 *User Prompts for Irrigation Loads*

User Prompts – Electrical Load for Data & Controls

After inputting information regarding irrigation, there are a variety of prompts regarding the power draws of various common sensors and controllers used in a vertical farm. The model currently includes: thermostat, CO_2 detector, nutrient doser, soil moisture sensors, PPFD meter, Wi-Fi router, computer, and computer monitor. The energy consumption of each individual IoT component is calculated by multiplying the power draw by the total number of days in one year, as these components will be on at all times.

User Prompts – Interior Heat Gains

Interior heat gains for lights were calculated using equations 14,15 and 16. The only user prompt required in this section was therefore the efficacy value for both the nursery and harvesting lights.

The user sets the net radiation at the crop surface value (Rad), by inputting the average PPFD provided to the plant canopy. The PPFD value (in μmols/m^{2}s) is converted into J/m^{2}d by multiplying by 0.22 (Lopez, 2021).

Evapotranspiration rates were adjusted by a pre-determined Kcb value. According to the FAO-56 guideline, the Kcb value for leafy greens is approximately 0.9, which was used to get final evapotranspiration rate in mm^3/s. Evapotranspiration is then converted into an hourly latent heat gain by multiplying the hourly moisture production rate by the latent heat of vaporization (2259.36 J/g).

User Prompts – Heat Losses

Two tables prompt the user for input information to calculate heat losses through the building envelope including the exterior areas, and thermal resistance of the wall assembly (Figs. 9 and 10)

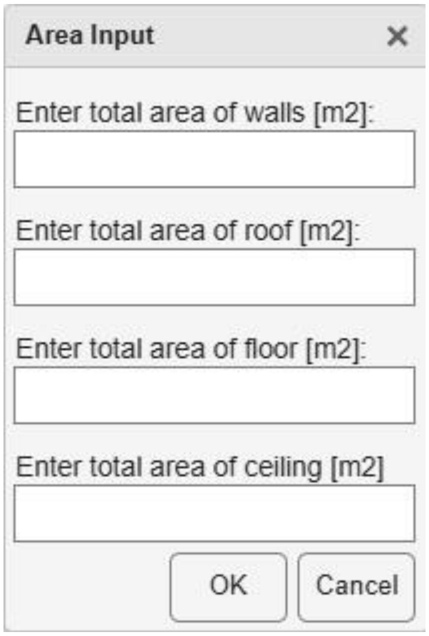


Figure 9 *Area Input*

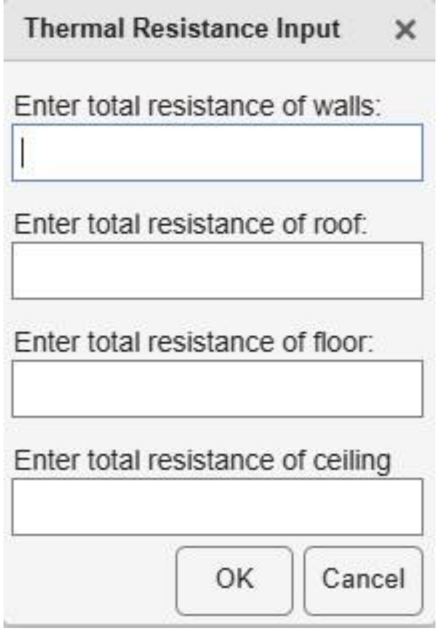


Figure 10 *Thermal Resistance Input*

For heat losses from infiltration, the user is prompted with a table of options to rate the air ‘leakage’ of the building (Fig. 11).

Figure 11 *Input screen of building leakage rating*

The answers to this prompt are associated with air change per hour (ACH) of air infiltration rate. “tight” was assigned an ACH value of 0.5, “average” a value of 2, and “leaky” a value of 5.

4.2 Experimental Procedure

An experiment was conducted in a pilot Smart Vertical Farm (SVF) at the University of Manitoba. The primary goal was to validate the energy model discussed in the previous chapter.

4.2.1 Description of Pilot SVF Facility

The SVF was a 2.3 m by 4.6 m grow room with an interior ceiling height of approximately 2.4 m (Fig. 12). The vertical farm had three exterior walls with exterior metal cladding, and a pitched roof. The roof was constructed with 2×6 studs and 3/8" SPF plywood sheathing, 6-mil CGSB vapor barrier, and 2 layers of rockwool insulation (about 12"). The walls and floor had the similar stud structure, but with one layer of rockwool insulation. The R value was approximately 48 for the roof, and 24 for the walls and floor.

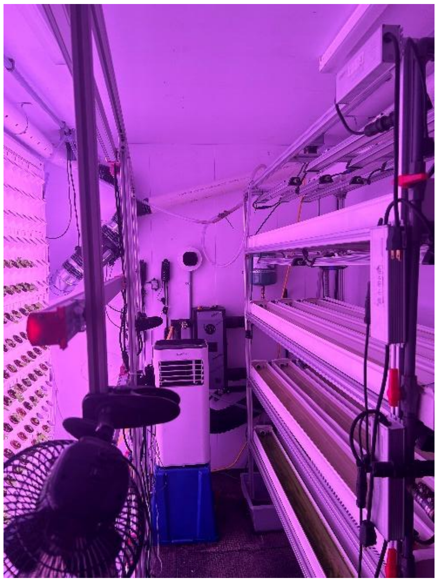


Figure 12 Smart Vertical Farm pilot facility

25. Electricity was supplied from the grid, and the farm has its own 50 amp panel.

The farm had a small nursery station underneath the farms' computer desk. The nursery station consists of two full spectrum sun blaster lights, which are controlled by a mechanical timer. The nursery station was a flood and drain table – a 64L container holds the nutrient solution and a submersible pump. The submersible pump was connected to a timer that is designed to flood the table on intervals set by the user (Fig 12).

Figure 13 *Nursery Tray Set-up Using Flood & Drain Table in SVF*

The irrigation setup consists of two 35-gallon food grade safe black tanks. Fresh water was stored in the bottom of the tank and filled the top tank manually using a submersible pump. Nutrients were added to the top tank based on EC readings from the blue lab pro controller. Water temperature and pH were also monitored using the blue lab pro controller.

Figure 14 *Harvest Today wall filled with plants*

The cultivation area consisted of a 360 Harvest Today wall (Harvest Today, Colorado). (Fig. 14). The Harvest Today wall was composed of individual tiles that had 6 ports each. Five of these tiles were stacked on-top of each other, and 8 across. The total number of ports on this wall was 360.

The Harvest Today wall was mounted to the side of the SVF facility. A submersible pump was located in the bottom of the tank and was programmed to turn on/off for 4 times per day 2 minutes per cycle. Nutrient rich water would therefore flow to the top of the wall and feed each port from behind – similar to a drip irrigation method. Each port consisted of a 51mm diameter hole that was designed to be filled with a 51mm cup. Ten Spectra Grow lights of the 60W SGL Slim model SpectraGrow, Inc. (Boston, MA, USA) were used in the cultivation room to supply an average light intensity of 250 PPFD. The lights were controlled by a mechanical timer. No dimmer was used for light control.

Heating was supplied by a hydronic system with a 3kW Thermo 2000 mini BTH (Thermo 2000 Inc., Quebec CA) electric boiler and a wall mounted radiator. There was a TACO variable speed pump supplying glycol mixed fluid to the radiator. The boiler was controlled by the EB-STATE7-01 Ecobee smart thermostat model (Ecobee Inc., Toronto, CA). This thermostat was programmed to have separate schedules according to when the spectra grow lights turn on.

A standalone 10,000 Btuh AC unit model number HCST07936 (COSTWAY, China) was used to cool the space. The AC unit operated on an internal thermostat.

An in-line duct 400cfm exhaust fan and intake fan (VEVOR, China) were located on the back (west) wall. Both fans were variable speed and were connected to independent controllers. The fans were set to turn on when humidity levels are above 75%. No CO_2 supplementation was used in the farm. A 60W oscillating fan (purchased from Canadian Tire, model number N.A.) was used to create adequate movement in the plant canopy.

4.2.2 Growing Procedure

Three crops were grown to validate growth rates, this included: kale, butter crunch lettuce and loose-leaf lettuce. These seeds are varieties commonly used by commercial farmers. Each nursery tray had 30 inserts, which were filled ¾ with moist coco-coir. Two seeds were planted in each insert, to ensure that enough seeds germinate. The trays were then immediately placed in the nursery station underneath the full spectrum sun blaster lights. The lights were set to 14h on 10h off cycles. The solution in the nursery station was maintained at an EC level between 1.0 – 1.5 mS/cm, and a pH of 5.5 – 6.0. The pump was set to flood the table for 40 seconds every 60 minutes, as the coco coir appeared to be an adequately saturated. Seedlings remained in the nursery station until they were ready to be transplanted (10 days).

After 10 days the seedlings developed a strong enough root-ball and stem to keep the plant intact in order to do the transplant. The new seedlings were transplanted into 51mm peat cups which were filled with moist coco-coir. The cups were then placed into the growing wall with the open slats faced upward to allow for water penetration. The spectra grow lights were set to a cycle of 16h on and 8h off, and were located approximately 18 inches from the plant canopy. The lights were turned on at 6:00 pm and turned off at 10:00 am. The nutrient solution was supplied to the growing wall (plants) 3 times per day for 2 minutes in each cycle. The nutrient tank was refilled daily using nutrient solution from a separate tank. A hose was run from the tank to the wall by gravity.

After approximately 35 days leafy greens were harvested from the wall and weighed on a kitchen scale. The average size was used to estimate yield and was used for the model calculations.

4.3 Data Collection

Yield and Environmental Conditions

Temperature, humidity and VPD readings were collected using a thermo-hygrometer from Govee Model no. H5179, with an accuracy of +/- 0.54ºF and +/- 3% RH. Airflow speed was measured manually using an anemometer. Electrical conductivity and pH were collected from the Bluelab pro controller, model no. BL-CONTPRO, which had an accuracy of +/- 0.1 pH and +/- 0.1 EC

(Bluelab Inc., New Zealand). Readings from the nursery station were manually taken using Alfred Horticulture pH and EC pens. The EC pen has a resolution of 1 uS, and an accuracy of 2%, the pH pen has a resolution of 0.1 pH and an accuracy of 0.2 pH. Alfred Horticulture products are distributed by Hort Americas, which has head quarters in Phoenix Arizona. Electrical conductivity was manually recorded on a weekly basis;

Light readings were collected using the MQ-100 Apogee quantum flux meter (Apogee Instruments, Utah). The flux meter was pre-calibrated and had a calibration uncertainty of 5%, and a measurement repeatability of 0.5%. Carbon dioxide concentrations were read from the HGC702854 Titan Controls CO_2 sensor, which has an accuracy of 5% (Titan Controls, Calgary, AB).

After plant mass was harvested it was weighed on the Presidents Choice, kitchen scale, which had a resolution of up to 1gram. Only the leaves of the plants were weighed, and they were not pre-dried.

Figure 15 *Alfred Horticulture Electrical Conductivity Meter*

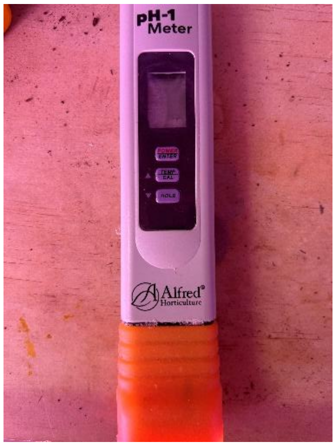


Figure 16 *Alfred Horticulture pH Meter*

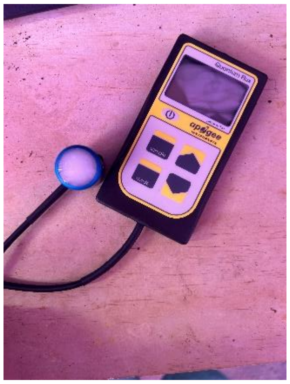


Figure 17 *Apogee Quantum Flux Meter*

Figure 18 *Titan Controls CO2 Sensor*

Figure 19 *Presidents Choice Scale Wet Mass of Harvested Leaves*

Energy Consumption

The EMV3A-2P-16 Emporia Energy Vue 16 sensors and energy monitor (Emporia Corp., Colorado, MA), was used to monitor electricity usage of the farm. The kit consists of 16 x 50A circuit sensors that were installed directly into the electrical panel. These sensors could read the 120V and 240V circuit lines on the panel. Figure 19 is a photo of the setup installed on the panel.

Figure 20 *Electrical Panel Set-up*

The information read from each sensor (circuit) was stored on the Emporia Energy app and analyzed on an hourly and monthly basis. Figure 20 is a sample of data collected on the boiler for December – January.

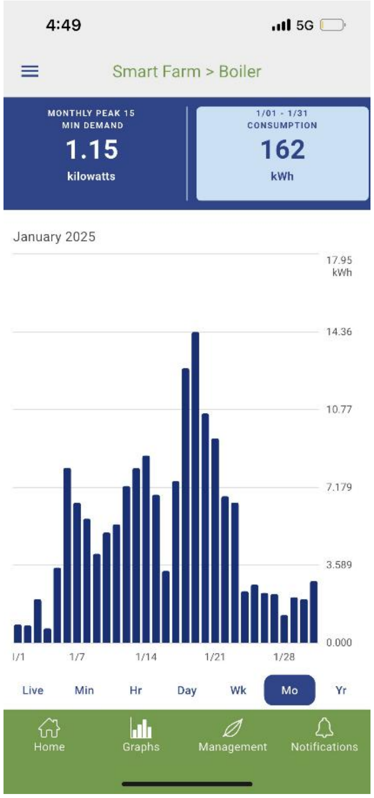


Figure 21 *Sample of Data Collected for the boiler by the Emporia Energy app.*

One of the issues of the circuit sensors is they measure the total energy consumed by all equipment on the same circuit. In the farm setup multiple appliances were connected to the same circuit, meaning it was harder to dictate the energy consumed for each sector. Therefore, in addition to the circuit sensors, 15-amp wifi smart outlet plugs provided by Emporia Energy, model no. SMT-OUT-1 were used to measure the energy consumption of specific appliances. The smart plugs were used to track the energy usage of; spectra grow lights, nursery lights, computer monitor and range extender, indoor air fans, submersible pumps and the AC unit.

The experiment involved two tests, running from September – October 2024 for a 35 day period, and from January - February 2024 for a 35 day period. Under these conditions kale, loose leaf lettuce and butter crunch lettuce were grown. Although the plants only grew for 35 days, data was collected for all of January, February, September and October.

4.4 Model Verification

To verify the model the user inputs to the model were matched with the experimental conditions(Table 3).

Table 3 *Summary of user inputs to model for validation*

Model Section	User Prompts	Model Variable	Value
Growing Conditions	System Selection	Gs	1 (Harvest Today Wall)
	Crop Number	CN	360
	Growing Area	A	2.58m2
	Ceiling Height	H	2.2m
	Crop	Crop	Loose leaf lettuce
Lighting	Power of Nursery Lights	Pl1	48W
	No. Of Nursery Lights	N1	2
	Power of Cultivation Lights	Pl2	60W
	No. Of Cultivation Lights	N2	10
	Hour on	Hon	18
	Hour off	Hoff	10
Irrigation	Power of air Pumps	Pa	0
	Run time of air pumps	Tia	0
	Number of air pumps	Ma	0
	No. Of water pumps	Mw	2
	Power of water pumps	Pw	100W
	Run time of water pumps	Tw	12min/d
Data Collection	Power draw of thermostat	Thermo	0W
	Power draw of CO2 monitor	Comon	5W
	Power draw of nutrient doser	Doser	10W
	Power draw of soil moisture sensor	Soilm	0W
	Power draw of PPFD meter	Lights	0W
	Power draw of Computer	Comp	5W
	Power draw of wifi router	Wifi	7W
	Power draw of range extender	Range	9W
	Power draw of monitor	Monit	5W
Heat Gains	Efficacy of nursery lights	Ee1	2.4 umol/J
	Efficacy of harvest lights	Ee2	2.6 umol/J
	Max temperature	Tmax	28
	Min temperature	Tmin	18
	Max humidity	RHmax	90
	Min humidity	RHmin	45
Losses	Area of exterior walls	Qb1a	28m^2
	Area of roof	Qb2a	11m^2
	Area of floor	Qb3a	11m^2
	R value of walls	Qb1r	3.5 W/m^{2}K
	R value of roof	Qb2r	3.5 W/m^{2}K

Model Section	User Prompts	Model Variable	Value
	R value of floor	Qb3r	3.5 W/m^2
	Assessed Leakiness of Building	ACH	2
Heating & Cooling Loads	Indoor fan power consumption		10

5.0 Results and Discussion

5.1 Experimental Results

Collected data is separated into monitored growth conditions throughout each growth cycle, as well as total measured energy consumption and consumption for each appliance used to maintain these conditions.

5.1.1 Environmental Conditions

The design temperature for the experiment was 22.0°C and the design relative humidity was 60%, which are the conditions commonly used in CEA facilities for the crops tested in this study. Under these conditions the VPD would be 0.90 kPa, which would be an optimal pressure to regulate the opening of the stomatal pores and assist with transpiration and nutrient uptake. The average temperature recorded for the experiment was 22.7°C, with large fluctuations from 18.0 to 27.7°C (Figure 21a).

The average measured humidity was 69.1%, with a range from 50.1 to 95.8 % (Figure 21b).

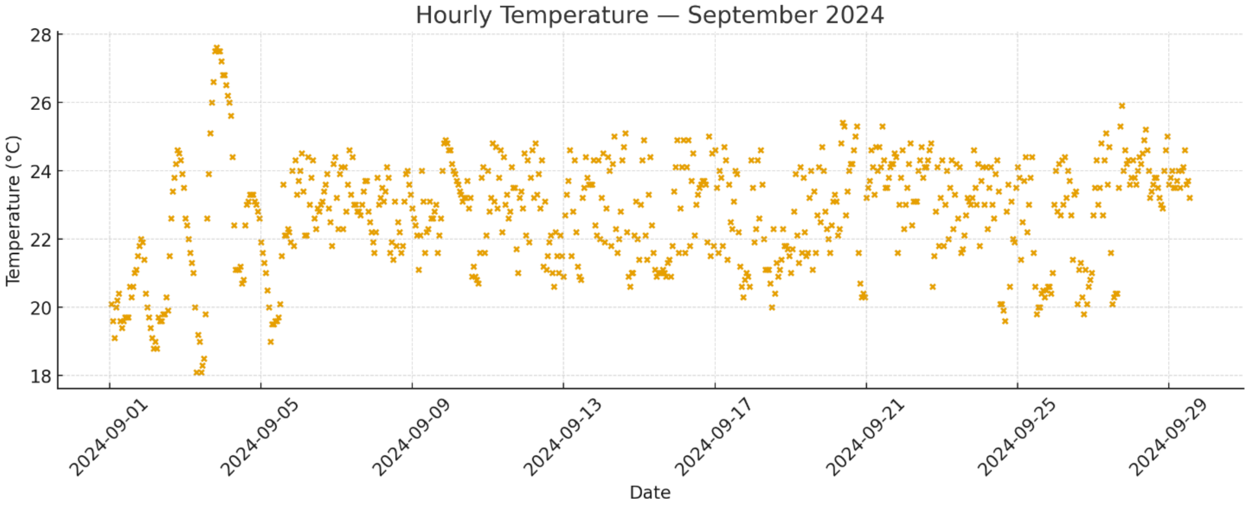


Figure 22(a) *Temperature Recordings September*

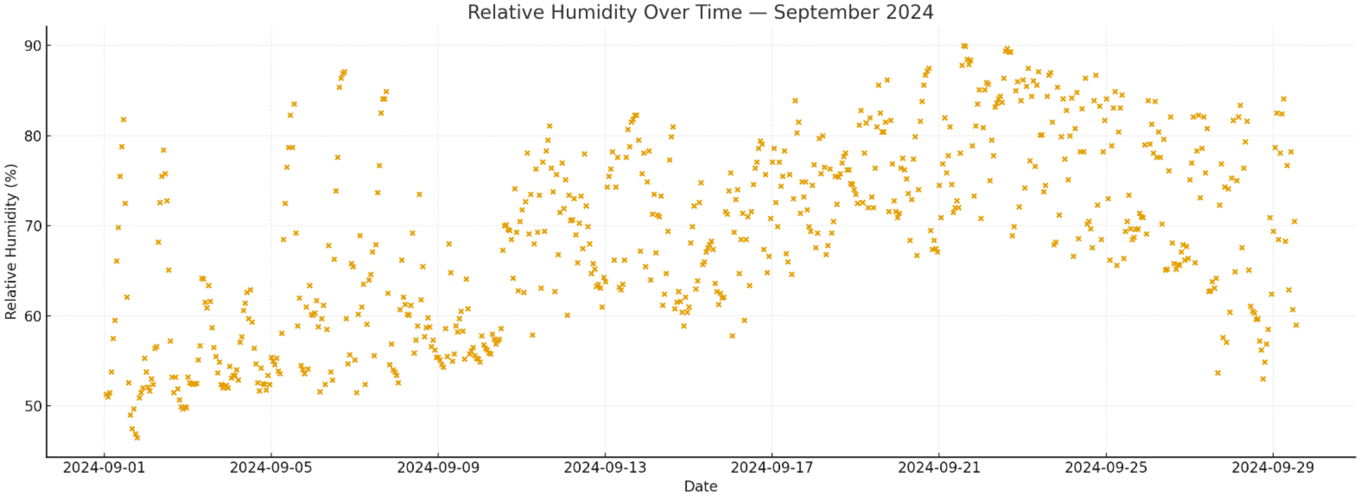


Figure 22(b) *Relative Humidity Recording September*

Figure 22. Recorded temperature (a) and relative humidity (b) for Test 2 readings from September 01 to September 29.

A possible cause of large fluctuations in room temperature and relative humidity was because smart climate controls were not installed in the test facility during tests. At the time of testing, the boiler and the AC unit were both controlled by independent thermostats, resulting in two appliances running at the same time. Another significant cause was the temperature overshooting by the hydronic heating system. Specifically, the supply temperature of glycol was fixed at 140ºF (60°C), which was the setting for the winter, but too high for the shoulder season. High temperature glycol resulted in the space heating up quickly and overshooting temperature ranges because the high temperature glycol in the radiator continued to emit heat to the room even after the thermostat had deactivated circulation pump of the hydronic system. Lastly, the hot air exhaust of the portable AC unit was connected to a 6” non insulated flexible duct to the outside, which caused some heat generated by the AC to remain trapped inside of the farm. Relative humidity peaked during the test period because the ventilation inlet was not large enough to provide the outdoor air to the farm to de-humidify the space. Additionally, the intake and exhaust fans included variable speed motors. During the beginning of testing, the motors were set to a low speed that could not efficiently dehumidify the space.

Based on the measured temperature and relative humidity, the VPD was calculated (Fig. 30). The average VPD was 0.85kPa while the optimal VPD values for leafy greens in their vegetative stage typically range from 0.65kPa – 0.97kPa. Due to the fluctuations of temperature and humidity, VPD as a result fluctuated as well. Large fluctuations of VPD can result in reduced crop productivity as crops are spending time adjusting to fluctuations in the environment (Inoue, 2021).

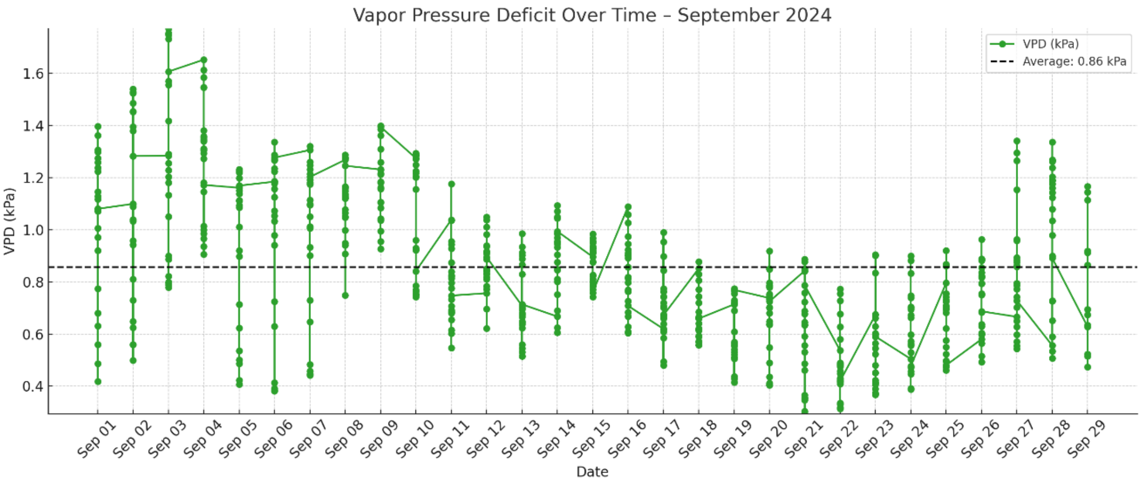


Figure 23 *VPD Recordings September*

Electrical conductivity values ranged from 1.2 – 1.7 for the testing period for both the nutrient tank and Harvest Wall. These values were an optimal range to provide an adequate amount of nutrients to the plant. An EC value higher than 2.5 can potentially lead to over nutrifying crops, whereas an EC value lower than 1.0, may not be sufficient in providing plants with the necessary amount of nutrients. Readings for pH also had a range from 4.5 – 6.0. There were times during testing where the doser provided too much pH down which caused slightly acidic readings. CO_2 values were also manually recorded on a weekly basis and ranged from 400 – 600 ppm. This was expected as CO_2 supplementation did not occur during the experiment. However, it should be noted that CO_2 was recorded when there was at least one person within the research farm. Therefore, readings may have been slightly elevated. Research has indicated that supplemental CO_2 (levels at 1000ppm) increases the rate at which plants photosynthesize and grow. Therefore, the CO_2 conditions maintained at this farm were not optimal.

Airflow was also measured at the plant canopy manually on a weekly basis and ranged from 1.2 – 1.5 m/s. This flow rate was deemed optimal.

Data collected from both sets of test is summarized in the table below. This shows the average temperature, humidity, VPD, EC and airflow.

Table 4 *Average Environmental Conditions Recorded for Two Trials*

Month	**Temperature (°C)**	**Humidity (%)**	**VPD (kPa)**	**EC (us/cm)**	**pH**	**CO_2 (ppm)**	**Airflow (m/s)**
Jan	21.9	65.4	0.89	1.5	5.5	480	1.3
Feb	20.5	67.6	0.88	1.5	5.4	480	1.3
Sep	22.7	69.1	0.87	1.6	5.9	550	1.3
Oct	23.4	68.2	0.86	1.5	6.0	500	1.3

5.1.2 Measured Energy Consumption

A summary of the measured energy consumption for each of the individual appliances is presented in Table 5.

Table 5 *Summary of Measured Monthly Energy Consumption by Individual Appliance*

Trial #	LED Grow Lights kWh	Water Pumps kWh	Nutrient Doser kWh	Computer kWh	CO_2 Mon. kWh	Boiler kWh	A/C kWh
1 (Sep)	308.5	1.3	0.9	3.1	4.0	65	282
1 (Oct)	319.6	1.4	1.0	3.2	4.1	252	106
2 (Jan)	319.6	1.4	1.0	3.2	4.1	162	0
2 (Feb)	310.2	1.3	0.9	2.9	3.9	93	0

The highest energy consumption were the LEDS lights in all four months of testing. LED lights roughly accounted for close to 50% of total energy consumption, which is in line with most commercial farms. The monthly energy consumption by LEDs varied little from month to month with an average of 315 kWh, as expected because the same lighting schedule was used for all four months. Overall this accounted for approx. 50% of total energy used in the vertical farm. The percentage of energy consumed by LED grow lights was in line with previous research studies. In a report prepared by the European Journal of Horticultural Science written by Orsini, et. al (2020) it was indicated that energy for lights requires 50-55% of the total amount used in an indoor vertical farm.

The second highest energy consumption was the AC unit in September and the boiler in October, January and February. The average temperature in September of 2024 was 20°C, with the lowest 5°C and the highest 31°C (Weather Spark, n.d). With the average outdoor temperature close to the set temperature of 22°C, minimum HVAC would be needed to achieve the set environmental condition. However, the LED lights generated significant amount of heat inside the room, and therefore the AC unit was operating frequently to cool the room, resulting in 282 kWh of energy consumption. Also, when the outdoor temperature dropped as low as 5°C, the boiler was turned on occasionally to heat the room, resulting 65 kWh of energy consumption, which was about 23% of energy consumption by AC cooling. A similar observation was made for October, but with energy consumption in heating higher than that in cooling – 252 vs. 106 kWh. The September-October data observations illustrated that both heating and cooling might be needed in vertical farming in climate regions like Winnipeg in the fall, and cooling was the main source of energy consumption in September and heating in October.

It should be noted that both AC and boiler energy consumption measure in this study might be an overestimate for actual vertical farms because of the control issues encountered in the test facility. As discussed in the previous section, the cooling and heating systems in the test facility were working against each other, mainly because of inappropriate control of the boiler. Specifically, the temperature of glycol in the boiler was too high (could not be controlled by the control system used) and emitted too much "residual" heat to the room after it was turned off, which obviously wasted heating energy but also required extra AC cooling energy to remove the extra heat.

In the winter months (January and February), the second highest energy consumption was heating (boiler) while the highest energy consumption was still LED lighting as the AC unit was completely off. The outdoor temperature fluctuated between -39 and 7°C, with an average of -10 °C in January. Measured heating energy was 162 kWh, which was about 50% of lighting energy consumption (320 kWh). In comparison with January, energy consumption in February was much lower - 93 kWh or 57% of that of January, but the outdoor temperature in February was very similar to January – it fluctuated between -42 and 9°C, with an average of -8°C. The lower heating energy consumption in February could be attributed to switching the schedule of the lights, and the thermostat schedule of the boiler. The lights were set to turn on at 18:00h in February in order to reduce the heating demand over night. Additionally, the thermostat schedule of the boiler was adjusted to turn off at a lower set-point. This was because due to the high supply temperature of the glycol, the boiler would occasionally over-shoot design temperatures. By adjusting the turn-off temperature point on the thermostat, the indoor design temperature was closer to 22^{o} C, while saving heating energy. Energy consumed by HVAC attributed to 22% - 52% of the total load. The HVAC loads for winter (22% - 33%) were in-line with the report published by Orsini et. all (2020) which stated that HVAC accounts for 30-35% of energy used in indoor farms. The HVAC loads used in September & October were much higher than what was expected, but this was due to the improper use of controls.

Energy consumed by pumps and controls equipment were close to negligible in comparison with lighting and HVAC, as expected. Altogether the energy consumed for controls and pumps on average accounted for 0.02% of the total load.

The highest total energy consumption occurred in September (665 kWh) primarily because both colling and heating were required in the fall (Table 5). Again, since smart controls were not used at the time of testing, the boiler would run independently of the AC unit, leading to higher HVAC consumption values. Additionally, the supply temperature provided by the boiler was adjusted for the winter test period. This meant that the boiler used less energy and did not overshoot temperature as easily as the fall test period, which led to the lower energy consumption in February.

Table 6 *Summary Measured Total Energy Consumption*

Trial #	Total (kWh)	Total per unit floor area (kWh/m^2)
1 (Sept)	664.9	63.3
1 (Oct)	687.3	65.5
2 (Jan)	491.3	46.8
2 (Feb)	412.2	39.3

The total area of the SVF is 10.5 m^2. During the winter, the SVF consumes on average 43.1kWh/m^2 per month. During the shoulder season the SVF consumes on average 64.4 kWh/m^2 per month. Therefore, the average yearly energy usage of the SVF is in between 517.2 kWh/m^2y - 773 kWh/m^2. These values are below reported findings from other studies, such as the literature review conducted by Miserocchi et. al (2025) which stated that energy consumption rates for vertical farms are in between 850–1150 kWh/m^2 per year. The overall kWh/m^2y value was lower in this test because of the cold climate of Winnipeg Manitoba. Beyond lighting, the next highest energy consumption factor indoor farms experience is cooling. This is due to the large amount of sensible heat that LEDs produce. Since Winnipeg is a cold climate, the additional heat from the lights actually significantly lowers the overall energy consumption of the farm. This is why the winter test produced a significantly lower overall consumption (43.1 kWh/m^2) than the shoulder season (64.4 kWh/m^2).

The average yield recorded in the experiment per port for looseleaf lettuce was 80 g, 45 g for buttercrunch lettuce, and 70 g for kale. Cycle days from seed to harvest were approximately 35 days. Cycles for re-harvesting leafy greens after the first cut were much shorter and took approximately 19 days. Yield projections for this experiment were taken using a 35 day cycle in order to get the most conservative estimate. From the measure yield per port, the total estimated monthly yield for looseleaf lettuce was 21.9 kg. Therefore, the average energy usage is 29.6 kWh/kg of looseleaf lettuce, and in fall the average energy usage is 43.9 kWh/kg. In a report published by Tech Brew, written by Jordan McDonald (2022), the average energy usage of a vertical farm is 38.8 kWh/kg of produce (2022). However, some reports have indicated much lower energy consumption values per kg of produce. A study conducted by Miserocchi et. al (2024) found the specific energy consumption for lettuce was 10-18 kWh/kg. An additional study by Lovat et. al (2025) found that a commercial vertical farm consumed 10 kWh/kg of lettuce.

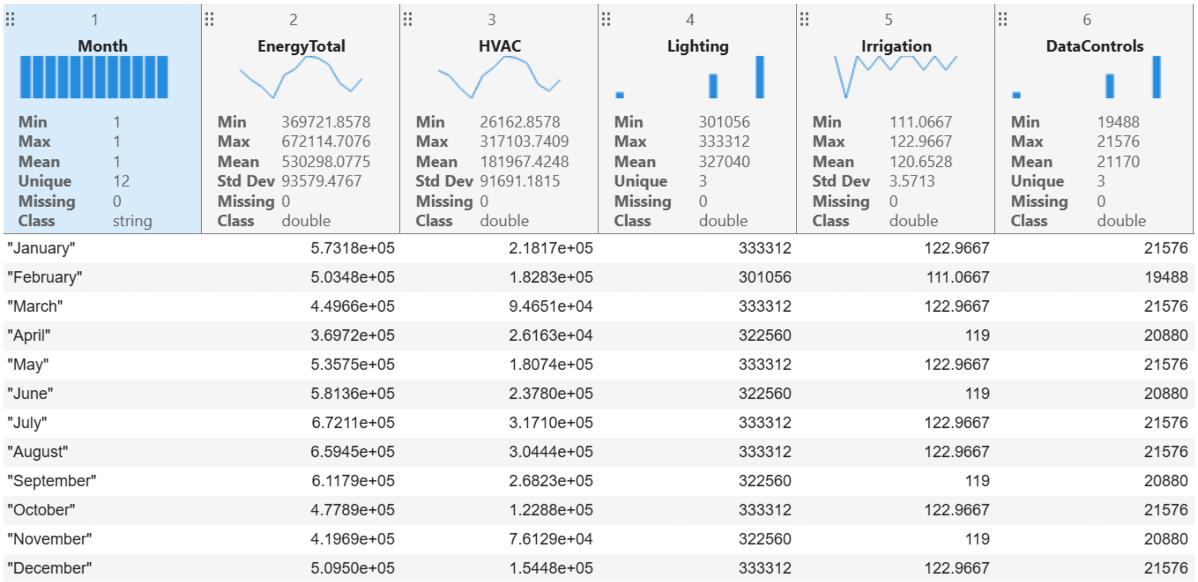
On average, the total amount of energy consumed was slightly higher per kg of produce grown than expected. Although the values found in this experiment were similar to past reports, the efficiency of the operations of the farm can be improved. As discussed, the main reason why these numbers are higher than expected is because no smart climate controls were used in the facility. This meant that optimal conditions were not maintained, leading to slower growth rates and smaller plants. Additionally, the variety of looseleaf lettuce selected was a shorter crop – resulting in less gram per port overall. Lastly, since HVAC equipment was not used efficiently, higher consumption values were experienced.

5.2 Model Verification

5.2.1 Model Predictions

Energy consumption for each month was calculated by the model in four different categories: HVAC, lighting, irrigation and data and controls. Figure 23 was pulled directly from the output tables calculated in MATLAB. The total energy calculated in MATLAB was done in Wh, therefore, to convert to kWh all of the values were divided by 1000.

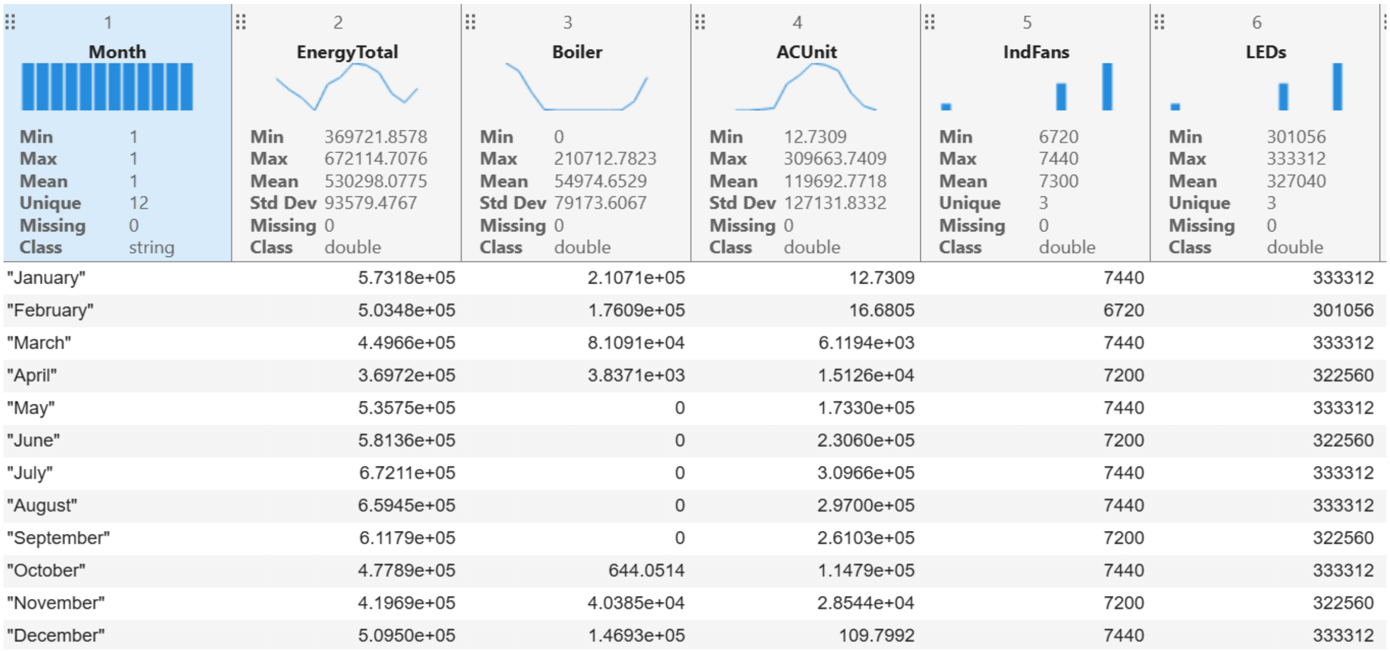
As seen in the model, the month with the highest total amount of energy predicted was July (672 kWh) and August (659 kWh). The model predicted that energy consumed by irrigation would be negligible (on average 0.12 kWh).



1 Month	2 EnergyTotal	3 HVAC	4 Lighting	5 Irrigation	6 DataControls
Min 1	Min 369721.8578	Min 26162.8578	Min 301056	Min 111.0667	Min 19488
Max 1	Max 672114.7076	Max 317103.7409	Max 333312	Max 122.9667	Max 21576
Mean 1	Mean 530298.0775	Mean 181967.4248	Mean 327040	Mean 120.6528	Mean 21170
Unique 12	Std Dev 93579.4767	Std Dev 91691.1815	Unique 3	Std Dev 3.5713	Unique 3
Missing 0	Missing 0	Missing 0	Missing 0	Missing 0	Missing 0
Class string	Class double	Class double	Class double	Class double	Class double
"January"	5.7318e+05	2.1817e+05	333312	122.9667	21576
"February"	5.0348e+05	1.8283e+05	301056	111.0667	19488
"March"	4.4966e+05	9.4651e+04	333312	122.9667	21576
"April"	3.6972e+05	2.6163e+04	322560	119	20880
"May"	5.3575e+05	1.8074e+05	333312	122.9667	21576
"June"	5.8136e+05	2.3780e+05	322560	119	20880
"July"	6.7211e+05	3.1710e+05	333312	122.9667	21576
"August"	6.5945e+05	3.0444e+05	333312	122.9667	21576
"September"	6.1179e+05	2.6823e+05	322560	119	20880
"October"	4.7789e+05	1.2288e+05	333312	122.9667	21576
"November"	4.1969e+05	7.6129e+04	322560	119	20880
"December"	5.0950e+05	1.5448e+05	333312	122.9667	21576

Figure 24 *Energy consumption predicted by model for four categories of operations*

Energy consumption for each appliance was also calculated by the model. Figure 24 was the output table created by MATLAB which summarized the energy consumption for each individual appliance. As energy consumption of all controls and pumps were calculated as negligible, Figure 24 only displays the energy consumption required by the AC unit, the boiler, indoor fans and the LEDs. These values were again calculated in watt-hours. The model accounted for higher cooling loads on an average monthly basis than heating loads. For example, it calculated that the boiler would account for 0 kWh for the months in between May – September, and the maximum requirement would be 210 kWh. Cooling however was calculated to be required for every month in the year (although a very low amount was calculated for January & February), and the maximum requirement was 309 kWh. There were no instances where the cooling load or the heating load was higher than the energy required by the LEDs. The LED load remained consistent throughout the year, on average energy required by LEDs ranged from 301 kWh (February) – 333 kWh.



1 Month	2 EnergyTotal	3 Boiler	4 ACUnit	5 IndFans	6 LEDs
Min 1	**Min** 369721.8578	**Min** 0	**Min** 12.7309	**Min** 6720	**Min** 301056
Max 1	**Max** 672114.7076	**Max** 210712.7823	**Max** 309663.7409	**Max** 7440	**Max** 333312
Mean 1	**Mean** 530298.0775	**Mean** 54974.6529	**Mean** 119692.7718	**Mean** 7300	**Mean** 327040
Unique 12	**Std Dev** 93579.4767	**Std Dev** 79173.6067	**Std Dev** 127131.8332	**Unique** 3	**Unique** 3
Missing 0	**Missing** 0	**Missing** 0	**Missing** 0	**Missing** 0	**Missing** 0
Class string	**Class** double	**Class** double	**Class** double	**Class** double	**Class** double
"January"	5.7318e+05	2.1071e+05	12.7309	7440	333312
"February"	5.0348e+05	1.7609e+05	16.6805	6720	301056
"March"	4.4966e+05	8.1091e+04	6.1194e+03	7440	333312
"April"	3.6972e+05	3.8371e+03	1.5126e+04	7200	322560
"May"	5.3575e+05	0	1.7330e+05	7440	333312
"June"	5.8136e+05	0	2.3060e+05	7200	322560
"July"	6.7211e+05	0	3.0966e+05	7440	333312
"August"	6.5945e+05	0	2.9700e+05	7440	333312
"September"	6.1179e+05	0	2.6103e+05	7200	322560
"October"	4.7789e+05	644.0514	1.1479e+05	7440	333312
"November"	4.1969e+05	4.0385e+04	2.8544e+04	7200	322560
"December"	5.0950e+05	1.4693e+05	109.7992	7440	333312

Figure 25 *Energy consumption predicted by model for individual appliances*

5.2.2 Comparison of Model Predictions with Experimental Data

Predictions of monthly energy consumption for September, October, January and February were compared with the experimental data for model verification. The relative difference was calculated as follows:

$$Relative\ difference = \frac{|Predicted - \ Measured|}{Measured} * 100 \qquad (30)$$

The predicted energy consumption rates calculated by the model were different from the measured results. The accuracy was particularly low for components with low power draws, however this contributed a negligible amount of energy, (such as pumps, computer, monitor etc). For instance, the relative difference between the modeled values for data and controls, and the measured values were in between 154 – 160%. However, this relative difference only accounts for on average 11.9 kWh. For irrigation, the relative difference between the model and measured results was around 91%, however again this is only equal to a difference of 1.2 kWh.

There was a low level of relative difference between the model and measured results for energy required by LEDs. On average the relative difference was only in between to 3 – 4.3%. The model performed best for HVAC calculations for September (relative difference of 22.7%) and January (relative difference of 36.9%). The model was not as accurate for predicting HVAC loads as it does not account for user inefficiencies and control issues in HVAC loads. For example, the model predicted 268 kWh of HVAC in September, but 345 kWh were used due to the boiler and A/C unit independent controls. The heating loads calculated in February (192 kWh) and in January (229 kWh) were higher than what was recorded. This may be attributed to higher heat gains than expected, and lower heat losses. The SVF was classified as average in the model, but the SVF may experience a lower ACH value than 2.

Table 7 *Comparison of monthly energy consumption by Sector*

	Lighting	Irrigation	Data & Controls	HVAC
September				
Model (kWh)	322	0.12	20.8	268
Measured(kWh)	308.5	1.32	8.09	346.9
Relative difference (%)	4.4	91.5	157	22.7
October				
Model (kWh)	333	0.12	21.5	122
Measured (kWh)	319.6	1.4	8.3	358
Relative difference (%)	4.2	91.2	158	65.9
January				
Model (kWh)	333	0.1	21.6	229
Measured(kWh)	319.6	1.4	8.3	167.3
Error Rate (%)	4.2	91.2	160	36.9
February				
Model (kWh)	301	0.11	19.5	192
Measured(kWh)	310.2	1.3	7.7	97.8
Error Rate (%)	3	91.5	154	96.3

Table 9 is a summary of the comparison of the measured and modeled energy draws for each individual appliance. As discussed previously, the largest percentage of errors came from calculating low draw appliances. One example is the difference in the energy draw of the monitor. The measured draw was significantly lower than the models' predictions because the monitor was primarily in sleep mode and had a power draw lower than it's operating consumption, which was the value used in the model. It should also be noted that the difference in energy consumption was still only 0.647 kWh of monthly usage which is also a negligible amount of energy.

The predicted energy consumption of the boiler was significantly higher than the measured values for January (by 60 kWh) and February (by 92 kWh), than the models' predictions. There are several potential reasons that could have caused these differences. Climate data for January – February of 2024 was not available from the NASA DAV program, at the time of testing. Therefore, climate data from the year before was used instead, which may have been from a colder period. Interior heat gains may also have been higher than what was accounted for in the model. The outside surface of the smart farm was categorized as aluminum sheet metal, so the solar absorptivity coefficient used was 0.3. This may have been an inaccurate value. Additionally, the lights have a reported efficacy of 2.8 µmol/J, but this value may have been different under practical uses. However, the opposite occurred for the September and October test period. The model estimated that the boiler would use 0 kWh of heating for September and only 0.7 kWh for October. The measured results were higher in this case strictly due to experimental error because the heating element of boiler was not turned off (as it should have been) during September and at the start of October. There was a significant amount of heat produced from the lights and enough insulation that the boiler was likely not needed. Energy consumption calculated by the model for the AC unit was consistent with what was recorded.

Table 8 *Comparison of monthly Energy Usage Results by individual Appliances*

Month	Water Pumps	Blue Lab Doser	Monitor	Comp	CO_2 Mon.	Ind. Fans	Boiler	A/C Unit
January								
Model (kWh)	0.1	0.7	0.74	3.7	4.4	7.4	222	0
Measured (kWh)	1.4	1.0	0.1	3.1	4.1	5.3	162	0
Relative difference (%)	91.2	22.9	695	18.2	6.8	38.8	37	0
February	0.1	0.7	0.7	3.4	4.4	6.7	185	0
Model (kWh)	1.3	0.9	0.1	2.8	4.0	4.8	93	0
Measured (kWh)	90.8	23	697	20.6	10	39	98.9	0
Relative difference (%)								
September								
Model (kWh)	0.1	0.7	0.7	3.6	4.3	7.2	0	261
Measured (kWh)	1.3	0.9	0.1	3.0	4.0	5.2	65	282
Relative difference (%)	90.9	22.6	700	18.8	6.4	39.5	100	7.5
October								
Model (kWh)	0.1	0.7	0.7	3.7	4.4	7.4	0.7	115
Measured (kWh)	1.4	1.0	0.09	3.13	4.12	5.3	252	106
Relative difference (%)	91.2	22.92	695	18.2	6.8	38.8	99.7	8.5

6.0 Conclusions

From measuring and monitoring the energy required for a Smart Vertical Farm (SVF) set-up in Winnipeg Manitoba, it can be concluded that it is feasible to operate vertical farms in these climates. To elaborate further the following key findings are listed:

1. Energy consumption by lighting accounted for the majority of energy consumed. The energy required by lights ranged from 46% to 75% of the total energy consumption in the SVF in this study.
2. Less energy was required to operate the SVF in the winter than in the fall or summer in regions with climate conditions similar to Winnipeg, Manitoba. This was due to not requiring cooling during the winter season, which requires significant amount of energy. The average energy consumption of the winter tests was 451.8 kWh per month whereas the average energy consumption of the fall tests was 676.1 kWh per month.
3. The energy consumption by the SVF per m^2 of floor area measured in this study was generally lower than the average of other vertical farms in different geographic regions reported in the literature. The estimated average yearly energy usage of the SVF is between 517.2 and 773 kWh/m^2y, in comparison to past studies indicating a range of 850–1150 kWh/m^2y.
4. The energy efficiency of the SVF could have been improved significantly if smart climate controls were used to optimize (synchronize) various HVAC components.
5. The energy model developed in this study performed well for calculating energy consumption by the lighting system (LEDs) but it was less accurate for calculating heating requirements. Further improvements could be made to the model to improve the overall accuracy.

Overall, the findings from this study proved that vertical farming could be adapted successfully to cold climates. The data collected from this research project could be used to provide practical benchmarks for improving energy efficiency in future designs and operations of smart vertical farming systems.

7.0 Recommendations

The data collected in this research project could be used to help shape future design and operational insights for other vertical farms in climates similar to Winnipeg Manitoba. The research conducted in this experiment is therefore important to build on, as methods to grow food in climate resilient structures are going to become increasingly important. Therefore, the recommendations to expand on this research are the following:

1. Measure energy consumption in a SVF that is maintained by smart controls. This should greatly reduce energy consumption, and improve yield, which will result in high energy savings.
2. Adopt energy-saving technologies in HVAC used for SVF climate control. Energy-saving technologies such as air economizers, can have significant reductions in cooling loads by using ambient air as a source of cooling.
3. Refine the energy model for heating and cooling load calculations. The model should be revised and re-tested once climate data for 2024 is available on the Nasa DAV Viewer.
4. Conduct additional trials of looseleaf lettuce with a different variety that grows to a slightly larger size. The variety selected in this experiment did not grow past 90g per port, however many growers experience yields of 180g/head of looseleaf lettuce. Using an alternative variety may improve the energy savings significantly.

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