University of Toronto

A Decision Support Tool for Greenhouse Design

ESC470: Energy Systems Capstone Proposal

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Executive Summary

Ontario's greenhouse production, mainly located in the southern part of the province, is expected to increase up to 50% over the next five years. With this production increase comes increased consumption of electricity, placing more pressure on Ontario's electricity infrastructure. It will be quite challenging to keep up with the projected demand increase from the greenhouse sector. Thus, there exists a design opportunity for greenhouse energy efficiency improvements to assist in mitigating the rising electricity demand while reducing costs for greenhouses. The greenhouse modelling program described in this report is a decision support tool, enabling growers and other stakeholders to evaluate and optimize greenhouse operation and performance. This tool is open-source and available to be modified, developed, and used.

Acknowledgements

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Last but not least, our sincere thanks to the entire Virtual Grower team, especially Jennifer Boldt and Kale Harbick, for answering our questions and helping us understand the intricacies of greenhouse modelling. The work we did in this project relied and built upon the modeling previously done by Virtual Grower.

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List of Acronyms

GHG	Greenhouse Gas
CO_2-e	Carbon Dioxide Equivalent
GWP	Global Warming Potential
USDA	United States Department of Agriculture
IESO	Independent Electricity System Operator
SL	Supplemental Lighting
HPS	High Pressure Sodium
DLI	Daily Light Integral
PPFD	Photosynthetic Photon Flux Density
LED	Light Emitting Diode
TOU	Time of Use

Introduction

Ontario's greenhouse sector is the largest in Canada, and it is growing rapidly [1]. According to IESO's Greenhouse Energy Profile Study, its production is expected to increase up to 50 % over the next five years [1]. Ontario's strong agricultural growth is accelerating the province's electricity demand and imposing challenges to its energy management. This opens up a design opportunity for greenhouse energy efficiency to assist in mitigating the rising electricity demand while reducing costs for greenhouses [2]. The goal of this design project is to inform the greenhouse grower's decisions around greenhouse operation and performance. In particular, this tool is focused on evaluating the greenhouse (GHG) emissions, electricity consumption, and cost associated with greenhouse operation or retrofitting.

Our team, Engineering Science Energy Systems 1T9, chose this project as it had the greatest opportunity for stakeholder interaction, learning, and impact. It was also important that the tool created be easily extendable and modifiable, in order to update it or to add functionality. When designing this tool, particular attention was paid to its user friendliness, user interactivity, and ease of extendibility.

Background

With Ontario having arguably one of the strongest and quickest growing greenhouse markets in both Canada and the US, a problem arises with meeting the significant energy needs of these operations. In 2019, the Independent Electricity System Operator's (IESO's) published call-to-action for innovative solutions to lower the demand of greenhouses in Ontario's market [1], [2]. The IESO projects that by 2025, there will be 1,300 MW of greenhouse load seeking to connect to Ontario's grid, straining the grid's electricity infrastructure and consequently necessitating a means to lower the energy intensity of greenhouses, and herein lies the engineering design opportunity this project aims to address [2]. To provide context as to the projected spike in greenhouse energy intensity, please refer to the subsections below.

Lighting

A key issue with greenhouses in general, and particularly in Ontario, is that of lighting, with low natural daily light integrals (DLIs) being a major limiting factor for greenhouse production during the winter months [3],[4]. From October to February in Ontario, natural outdoor DLIs ranged from 5 to 15 mol/m^2/d when some crops need as high as 25 mol/m^2/d, leaving a low number of photosynthetically active photons required for optimal product quality and yield in certain plants [5]. Regrettably, monthly DLI data for Ontario is not publically available, so an extrapolation may be necessary from the heat map of the average monthly outdoor DLI for the United States of America, as seen in Figure E-1. With greenhouse glazing and structural materials leading to additional transmission losses of up to 60% of DLI, high quality winter-grown produce in Canada can require considerable artificial lighting provisions and consequently, considerable electricity use. To compensate for this, extra lighting is required; as seen in Figure E-2 below, greenhouse lighting in Ontario accounts for the majority of electricity use in greenhouses, taking up over 700,000 MWh in 2018 alone.

Supplemental lighting (SL) is commonly used to maintain crop productivity and quality during low DLI periods however, the optimum SL light intensity is still yet to be determined [3], [1]. With the increasing demand of vegetable and fruit growers in Ontario due to an increase in food demand, the square footage of vegetable and fruit greenhouses all over Ontario with lighting is projected by the IESO to double from its current four percent to eight percent by 2024 except in the city of Essex, where the footage expected to exponentially increase to 29 percent of the total greenhouses in the region [1]. From the types of SL available, the IESO recommends LEDs for their energy efficiency advantages, saving roughly 35-55% of energy when compared to the high pressure sodium (HPS) lights, which are the currently accepted SL used in greenhouses.

However, there are some barriers to adopting this technology, such as a high upfront cost, the learning curve associated with this lighting (as stated previously, the optimum exposure for each plant is still not known), and the uncertainty of savings (with lighting suppliers providing inconsistent figures to customers) [4]. HPS lighting is still the predominant choice of SL for greenhouse growers in Ontario, in spite of its apparent energy intensity, leaving greenhouse growers an ultimatum between which lighting source they choose to employ for their produce [4]. The importance of this decision is heightened by the knowledge that SL has only recently been adopted by vegetable greenhouses (growing produce such as cucumbers, tomatoes, etc.) in Ontario and because of this recent adoption, the full potential impact of SL on the grid has not yet been realized. The IESO projecting that by 2024 the electricity consumption of greenhouses will increase by nearly three fold, and peak hour demand increasing by 552% [4]. The main reason for this is that the majority of commercial greenhouses in Ontario currently receive no SL but are expected to adopt this technology and consequently, a great spike in electricity demand is expected for lighting, which is still only one area of the energy demand spike expected for greenhouses in Ontario.

Heating Demand from Greenhouses to Grid

Though the highest growth in energy demand in greenhouses is to be caused by lighting, heating from natural gas takes up the majority of the energy demand within a greenhouse and consequently, lowering the energy required from the grid to heat a greenhouse effectively will also achieve the IESO's goal of preventing greenhouse demand from straining Ontario's energy grid [4]. As to the application of natural gas in vegetable and fruit greenhouses, the majority of it goes toward keeping the greenhouse adequately heated such that plant growth, quality and yield are not negatively affected by Ontario's cold winter conditions, which is observable in Figure E-3 below [4]. With the energy consumed by greenhouses in Ontario projected by the IESO to increase to between 12 and 16 TWh by 2024, energy efficiency for peak shaving and the importance of a more environmentally friendly means of energy generation for greenhouses become apparent, giving way to the discussion of a net-zero industrial scale greenhouse [4].

The IESO outlines multiple possible means of alternate energy innovative solutions for Ontario's grid, though they are not discussed in length within the Posterity report that mentions them [4]. These alternate means of heating energy generation include: greenhouse-integrated solar photovoltaics, thermal energy storage via heat pumping, hybrid generation and storage, or microgrids [4]. With the sheer variety of available options, there is an opportunity to inform growers of their energy savings potential and of their suitability to a growers' greenhouse designs, especially considering the possible shortage of natural gas for heating in greenhouses in the near future.

Although many greenhouse generators desire natural gas service contracts that provide a fixed supply of gas for their annual demand, these desired "firm" contracts cannot often be provided due to limited natural gas infrastructure and although natural gas pipelines are being built to increase supply, it is likely that "firm" contracts will be a rarity for the foreseeable future [4]. As natural gas is mostly used to heat the greenhouse and supply in Ontario may not adequately supply this growing market in the future, one must ask if an alternate design exists to maximize heat retention and minimize energy use, which may be answered with a passive solar greenhouse [4], [6]. Therefore, the aforementioned alternate means of energy generation are captivating options to investigate in mitigating the energy demand from heating.

Overall Effect of Greenhouses on Grid

In 2018, the annual energy consumption of greenhouses in Ontario was approximately 7.5 e-TWh of energy, the majority of which came from natural gas and most of the rest from electricity (73% and 18% respectively) [4]. As seen in Figure E-4 below, over 5 e-TWh of energy is consumed by vegetables and fruits, with flowers and potted plants and cannabis combined not totalling even half of this amount [4].

Summary and Addressing the Gap

Ultimately, the vast array of options with no distinct correct answer available in Ontario's growing market leave considerable uncertainty when viewing the situation through the lens of a prospective or current greenhouse grower. There are several important decisions to be made:

1. Would the higher cost of LEDs be worth the apparent superior efficiency when HFG lights are the current proven method?
2. Are tomatoes, peppers, cucumbers, or cannabis the ideal plants to produce in Ontario, each with unique operating conditions?
3. Will a traditional or passive solar greenhouse be used when both offer distinct advantages and disadvantages (though one is more proven to work than the other outside of studies)?

Ironically, it is these differing choices that expose the gap which a decision-making tool to assist growers in making a decision can fill rather than an overt flaw in a specific design parameter or design choice. Such a decision-making tool will have to reflect the general values a greenhouse grower in Ontario would realistically have in its design, which is where the importance of reasonable and actionable objectives comes into this document. With the picture of Ontario's market and the opportunity for design that it provides illustrated in the literature review above, the aim of how the proposed design means to meet this opportunity is elaborated upon in the Objectives section later in the report.

Reference Design: Virtual Grower

Virtual Grower, built by the US Department of Agriculture (USDA), is a decision support tool for greenhouse systems. This greenhouse modelling software simulates heating costs, energy use, and the impacts of supplemental lighting on plant development. Primarily focused on the United States, Virtual Grower predicts crop growth for multiple varieties of flowering plants [7].

At start up, Virtual Grower allows the user to set the location of the greenhouse to be modeled. This pulls in geographic weather information from the National Renewable Energy Laboratory. Next, the user inputs the structure of the greenhouse as well as the materials used in its construction. A schedule for heating and a heating system can then be selected. The location-based weather parameters and humidity are used to calculate the heat loss through conduction, convection, and radiation, and thus, the heating requirements of the greenhouse. The lighting costs for a greenhouse utilizing supplemental lighting are calculated based on the number and wattage of lamps being used, the number of hours per day supplemental lighting is on, and the cost of electricity. This tool also emphasizes bio-physical simulation models that predict plant growth, development, and yield. Overall, Virtual Grower allows for great flexibility with building multiple unique greenhouse structures, defining different heating systems and schedules, lighting systems and schedules, and growing different mixtures of plants [7].

The decision support tool built in this capstone project is significantly different from the USDA's Virtual Grower software. The tool:

1. Focuses on greenhouses in Ontario (particularly in the municipality of Leamington, Essex County)
2. Models the growth of Ontario's most crops including cucumber, pepper, tomato, and cannabis
3. Models the overall energy and electricity consumption of the greenhouse's heating and lighting systems
4. Models the use of energy storage systems to manage demand, particularly for load-shifting and load-levelling or cost reduction

Model Design

Objectives of The Model

The decision support tool is made to address the variety of options available and parameters to consider for greenhouse growers in Ontario when choosing a greenhouse design, by providing a simulation model of an Ontario greenhouse that inputs varying design parameters to reflect their impacts on users' objectives. The primary objective of the design project is to develop a model for greenhouse operation and performance to inform the greenhouse grower's decisions. The model can lay the foundations surrounding the energy solutions and efficiency improvements they can employ to optimize their greenhouse performance.

The model considers several inputs to simulate greenhouse operation and performance, including (but not limited to) (Figure 1):

- Crop Type
- Greenhouse Structure
- Energy Storage Options (including storage type, power capacity, and energy capacity)
- Heating Fuel Type
- Photoperiod (start and end time)
- Material Used

Using the above inputs and a variety of simulation algorithms, the model outputs the following (Figure 2):

- ***Burden On the Electricity Grid***, a measure of electricity consumption reported as peak power (W) or total energy used (Wh)
- ***Greenhouse Gas Emissions Related to Operation***, a measure of the Global Warming Potential (GWP) from the combined impacts of CO_2, N_2O, and CH_4 reported as g CO_2-equivalent
- ***Cost Implications of Decisions,*** a measure of the capital and operating expenses related to greenhouse operation reported as ($)

It should be noted that the purpose of the model is not to provide an overall score to determine which parameters perform objectively better, but rather to characterize the impacts of various input parameters on the desired performance criteria. The model will empower the user to contextualize the results and make more informed decisions for their greenhouse.

In addition to providing potential insights into the optimization of greenhouse operations, an additional purpose of the model is to serve as an educational tool. If successful, the project will result in a model that can provide engineering students with a deeper understanding of the intricate systems within industrial greenhouses, as well as techniques in effectively modelling such complex systems.

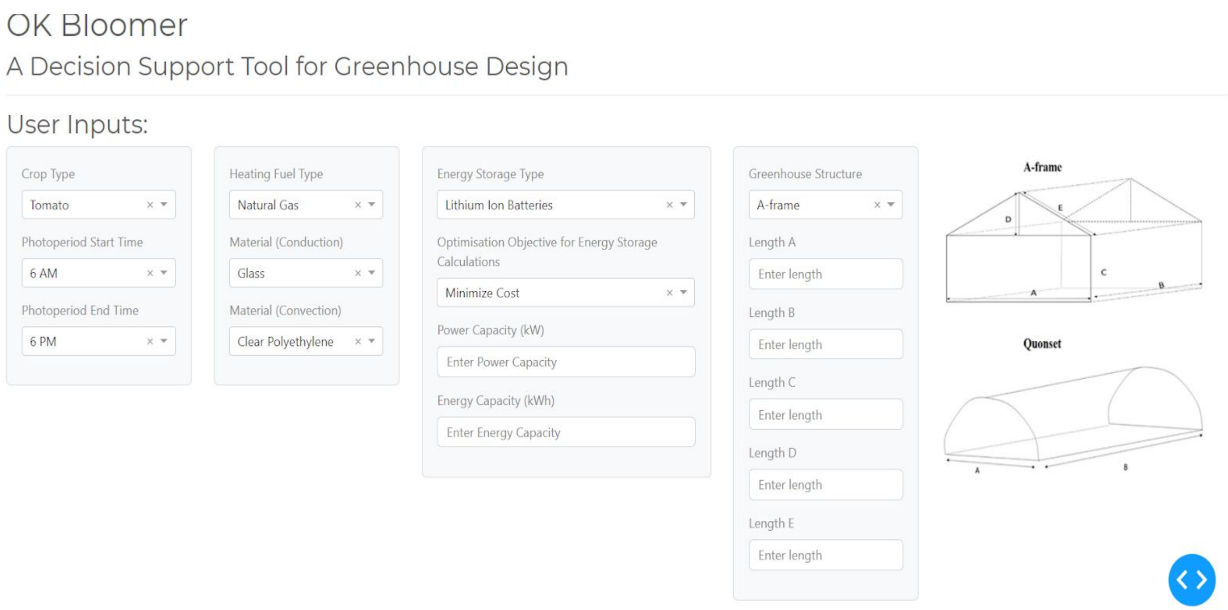

Figure 1. User Inputs

Figure 2. Outputs

Design Values

When building this decision support tool, the design team particularly valued:

- ***User Friendliness,*** referring to the tool's simplicity and ease of use
- ***User Interactivity,*** referring to the tool's ability to allow the user to interact with and explore the data from the modelling simulations
- ***Extendibility,*** referring to the ability easily update, modify, or add new functionality to this tool

Stakeholders

Table 1. Key Stakeholders and their Interests

Stakeholder	**Interests**
Greenhouse Growers	May be interested in a modelling tool that can optimize greenhouse operation and performance, particularly by reducing cost, GHG emissions, or energy use
IESO	May be interested in a modelling tool that can support further understanding of Ontario energy needs, particularly in a fast growing sector such as this one
Government of Ontario	May be interested in a modelling tool that can support further understanding of Ontario energy needs and policy-making
University of Toronto Faculty	Interested in the educational growth and outcomes of students in ESC470, particularly in their engineering design skills and their understanding of the engineering design process
Capstone Team	To learn and create a working greenhouse modelling tool
Future Students	To learn from the process, and continue the development of the model as independent projects

Software Design and Architecture

1. ***Backend***: Python is chosen as the modelling language, and this design decision ties to the team's value to design for extendibility. Python is one of the most popular programming languages in the engineering undergraduate curriculum and one of our project stakeholder groups is the prospective Engineering Science students in the Energy Systems option. Therefore, programming the model in Python allows for the ease of future modification for those who wish to learn from and build upon this greenhouse modelling project.

2. ***Frontend***: Plotly Dash is chosen as the data visualization library to design the frontend user interface, and this design decision ties to the team's value to design for user experience and interactivity. Plotly Dash is a Python library; therefore, it integrates well with the backend. It offers interactive plotting and allows users to design a website in Python environment. In addition, Plotly Dash allows multi-input and multi-output visualizations and parallel callback functions, which enable vast flexibility for customization and fast computation for backend simulation [8, 9].

3. ***Modularized Architecture***: A modular software design is adopted, which separates the frontend and backend codebase, and within the backend simulation, each simulation module (such as lighting, heating, and energy storage) are organized into different Python files with functional calculations further organized into Python functions. In the frontend codebase, outputs are grouped together if they share the same inputs, and then parallel callback functions are used to enable faster calculation and output display. Figure 3 depicts the software architecture of this project.

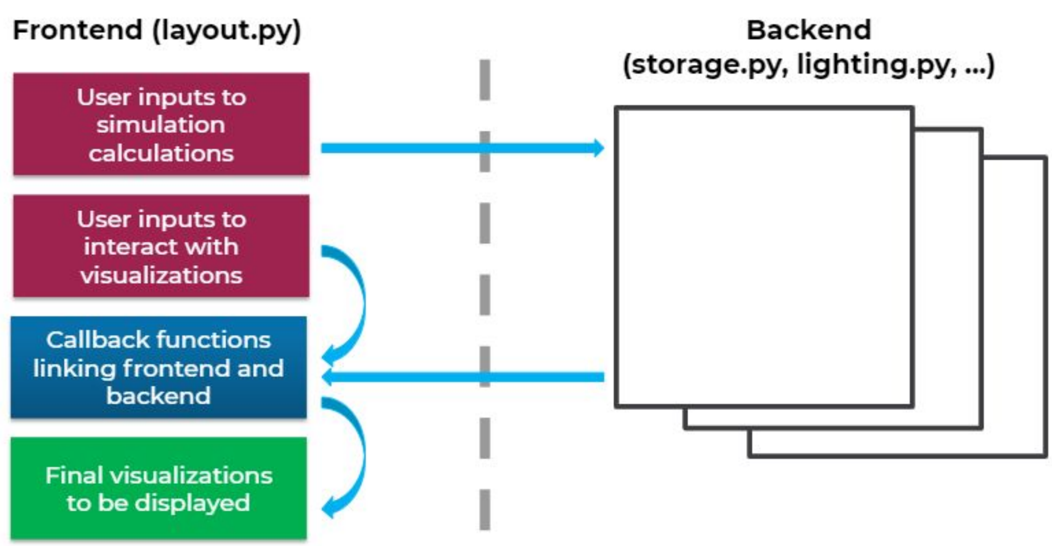

Figure 3. Software Infrastructure

4. ***Open Source Project***: This project is designed to be an open source Github repository. The modularized simulation algorithms allow users to understand and modify the model more easily. In

addition, users can also modify the data provided in the dataset folder to further enhance the model if they wish.

Modelling Decisions and Critical Assumptions

Modelling on Annualized Basis

The chosen timeframe for the model is 1 year due to interpretability, and because it is the smallest block of time able to fully capture ambient variation. Inclusion of seasonal variation was deemed necessary as the changing external conditions showed significant potential to impact the model results, primarily due to the heating requirements of the greenhouse.

The finalized granularity was chosen to be hourly, meaning that all resource requirements are calculated on an hourly basis. Modelling hourly is standard practice in power systems, as most meters capture record data to this degree. This is an important consideration for the design, as one of the drivers of the project is a desire to understand the behaviour of the greenhouses from the perspective of the power grid. Hourly data is the most intuitive granularity to show consumption patterns changing throughout the day, adding to the interpretability of the outputs. Ambient data, such as temperature, wind, and solar data, was available up to this granularity, further supporting the case for hourly modelling.

While it would have been possible to model a year as 8760 unique hours, this was deemed problematic as it would convey a level of precision that is not backed up by the methodologies at this time. Including every hour of a year as a unique state would imply that there is confident data justifying the differences between these unique hours to a degree that simplifying the model to include fewer unique states would lose valuable resolution. While the data for ambient conditions does include 8760 unique data points, the data should only be interpreted as a representative sample, because the actual ambient variations throughout the year would be unknown, and would almost certainly not adhere to the precise patterns shown in the data. This led to the final decision in the timeframe modelling; the creation of one representative day for each month of the year. Energy usage was tracked hourly for the 12 representative days, and each month was then reconstructed by multiplying the values by the number of days per given month. Using this method, only 12 days needed to be calculated as opposed to 365, speeding up the runtime and aiding the development of the initial model.

Removing Bio-Physical Simulation of Plants and Yield as a Model Output

The bio-physical simulation of plants requires a thorough understanding of the impact of a number of parameters such as temperature, lighting, humidity, irrigation, soil nutrients, and supplemental CO_2 on plant growth and development. It also requires an understanding of the various feedback effects involved when these parameters are varied. For instance, leaf growth and expansion may be dependent on temperature, light, water, photosynthetic efficiency, and nutrient availability, and is likely unique to each species. Leaf expansion will have feedback effects including water loss from transpiration and increased net photosynthesis of the plant. Leaf expansion and its feedback effects are only one aspect of modelling plant growth and yield; there are many more aspects to be considered, all of which are just as complicated. Thus, modelling plant growth is a difficult, highly dynamic field that requires extensive study, and the team abandoned this modelling strategy.

To approximate plant growth, a statistical approach was also considered. This approach attempted to model crop growth and yield based on previously reported values. However, research found that there was a high degree of variability in reported results (as seen [10] and [12]), making it hard to model yield with accuracy.

Having exhausted these modelling approaches, the team determined that the unique value add of this decision support tool was centered around the simulation of electricity and energy use, and the ability to evaluate the impact of an energy storage system on these parameters. Therefore, in order to focus our attention on this primary objective, plant growth modelling, and thus, yield as an output were eliminated.

Design Process

The design of the software architecture allows the team to have an easy-to-follow design process, as depicted in Figure 4. During each iteration of design, the team starts with research and scope the outputs to be displayed from the simulation. The backend and frontend development then take place in parallel, followed by the integration step and verification and validation testing.

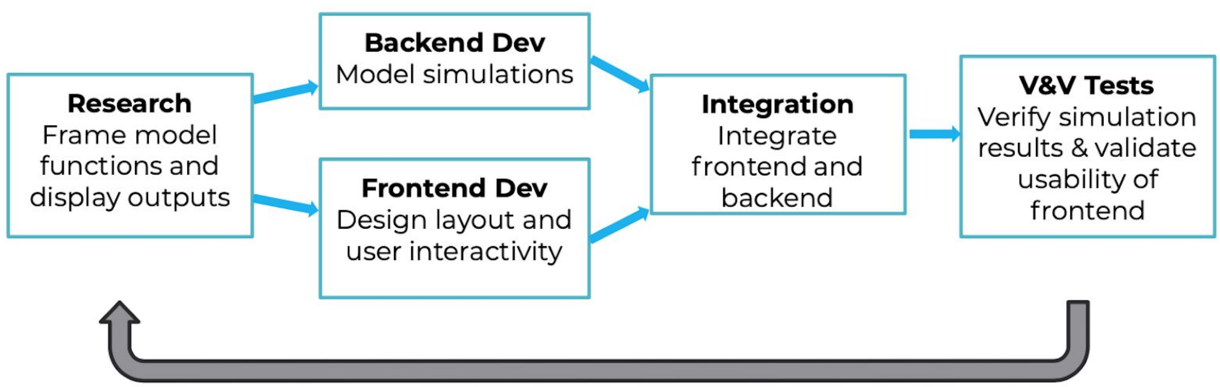

Figure 4. Design Process

Model Functionality and Modules

1. Greenhouse Structure

Research and Data

With the structure of a greenhouse having a significant effect on the structure's efficiency and productivity, the possible choices had to be integrated into the model back-end. There are multiple commercial greenhouse structures that may be chosen for construction, with the majority being categorized into gutter-connected, free-standing quonset, or free-standing gable (A-frame) [12]. Although the model in its current iteration has crop yield scoped out, the area of the greenhouse (dependent upon its structure) influences its rate of heat loss, expressed as an equation below.

$Q = A * U * \Delta T$ [13]

In this equation, A is the exposed surface area, U is the heat loss constant (unique to the materials used in the greenhouse's construction), and ΔT is the difference in temperature inside of the greenhouse against ambient outdoor conditions. Therefore, for the model to effectively simulate heat loss the greenhouse's area had to be accurately calculated.

A difficulty in integration arose when it was observed that multiple sources presented multiple different means of calculating the effective area of a greenhouse, as seen in the differences between the Purdue University and the ACF Greenhouse equations for calculating the area of the same type of greenhouse [13], [14]. To ensure consistency in the results and because it was from an accredited institution, Purdue's means of calculating the greenhouse area was used in this model and is pictured in Figure 5.

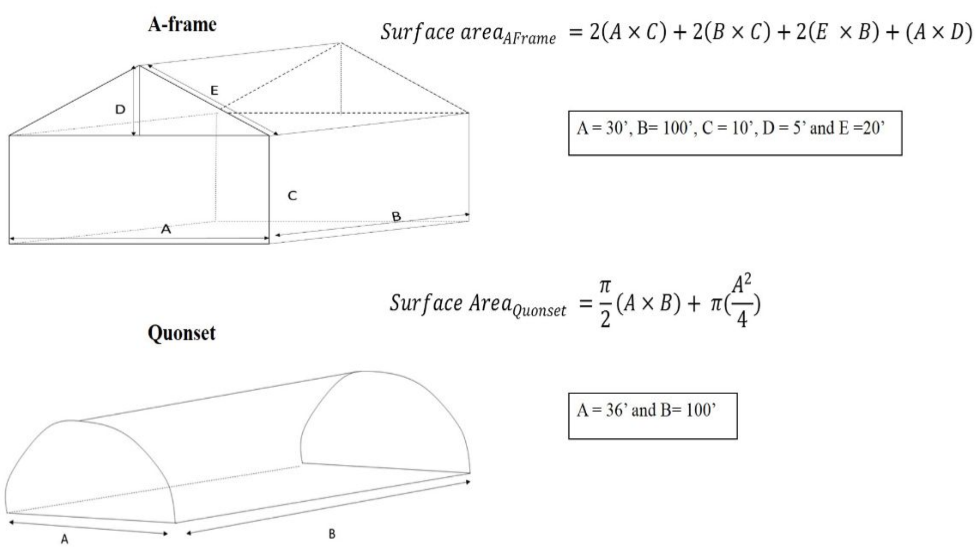

Figure 5. A-Frame and Quonset Greenhouse Structures [13]

The data required for greenhouse area calculations includes the following:

1. A-Frame greenhouse dimensions as shown in Figure 5
    a. The dimensions for A, B, C, D, and E are to be input by the user.
2. Quonset greenhouse dimensions as shown in Figure 5
    a. The dimensions for A and B are to be input by the user.

Inputs and Outputs

As stated above, the user selects the dimensions of their greenhouse structure of choice from a drop-down menu in the front-end user interface, which then implements its respective calculation function in the back-end code.

There are two functions being used depending upon the user's selection of a greenhouse structure in the front-end: one function each for the A-frame and quonset options respectively.

The A-frame function's inputs and outputs are as follows:

- Inputs:
    - A, B, C, D, and E in metres as displayed above in Figure 5 input by the user
- Outputs:
    - The surface area (m^2) of the greenhouse based upon its dimensions and the following formula:
    - $Surface\ Area\ =\ 2(A * C)\ +\ 2(B * C) + 2(E * B)\ +\ (A * D)$

The quonset function's inputs and outputs are as follows:

- Inputs:
    - A and B as displayed in metres as displayed above in Figure 5
- Outputs:
    - The surface area (m^2) of the greenhouse based upon the following formula:
    - $Surface\ Area\ =\ (\Pi/2)(A * B)\ +\ \Pi(A^2/4)$

Assumptions

Only Free-Standing Quonset and A-Frame Designs Apply

For this iteration of the code, only freestanding A-frame and quonset greenhouses were chosen, mainly due to the higher complexity that model would inherit when accounting for connected greenhouse structures without gaining improved functionality aside from extra choices for the user; an omission made due to time constraints requiring prioritization for other functions in the model.

Greenhouse is Filled with Maximum Number of Crops

Another simplification to greenhouse structures was that the area calculated would be divided by the spacing required by each crop type to determine the amount of plants that can fit within the greenhouse, implying that the greenhouse is completely filled with crops without walking space. This assumption was made to assume a maximum case of crop production, although other scenarios (minimal crop production, crop production changing per season, etc.) may occur. Addressing these simplifying assumptions and omissions are likely paths for future teams to take when attempting to improve this model.

Next Steps

For the greenhouse structure, other designs may be coded in the back-end such that the user will have more options to choose from in the front-end drop-down menu in addition to the current A-frame and quonset options. For instance, the addition of gable connected structures will make the model applicable to more growers.

Furthermore, the simplifying assumption that the greenhouse is filled with the maximum possible number of crops could be replaced by the user being able to input the number of their chosen crop grown within the greenhouse directly into the front-end, limited by the maximum number of crops that the greenhouse could fit in. The main reason for assuming that the maximum possible number of crops would be grown was that there was no way to tell that the user was growing too few to be profitable without research to predict the profit to be gained from crop yield. Should the user be able to input the crop number, the model should either assume that the grower's judgement is sound for their chosen number of crops or read from a data sheet of expected profit from individual crop yield and inform the user of this profitability.

2. Crop Choices

Research and Data

Ontario's greenhouse market has several viable options for growers when it comes to plant choice, with cannabis, tomatoes, cucumbers, and peppers all providing lucrative possibilities. The majority of the harvested area of vegetables and fruits in Ontario falls to peppers, cucumbers and tomatoes, which take up millions of square metres of harvested area (see Table E-1 below for further details) and have increased in area as demand has increased [4], [5].

In addition, these three plant types draw three quarters of Ontario's profits for exports, and two thirds of the total exports as well, with demand increasing for each since 2013 as observed in Table E-2 below [5].

Cannabis, however, is not as widely grown as fruits and vegetables like tomatoes, cucumbers, or peppers but it has been an emerging produce in Ontario since legalization in 2018 [4]. As of 2019, the cannabis industry in Ontario consists of 340 greenhouses, supports 5,700 jobs, earns $930 million (projected to increase to $2.38 billion in 2021), and is expected to be the largest cannabis market in Canada, though demand as of 2019 still cannot be met [4]. The majority of cannabis production occurs in greenhouses, with outdoor production being so rare as to be negligible [4]. The land allocated to cannabis in Ontario is expected to jump to 16,000,000 square feet in 2024, demonstrating the potential for expansion and industry support for this new produce [4]. There are other key differences between cultivating cannabis, tomatoes, peppers, and cucumbers as expressed in Table E-3 below. Although the high DLI required for cannabis relative to the other given options necessitates a higher amount of energy dedicated for lighting, the most energy intensive means of energy production for greenhouse growing in Ontario for each option remains to be heating [4]. With the electricity and overall energy demands of a greenhouse in Ontario examined in the analyses above, it begs the question as to the effect on Ontario's grid that greenhouses inflict and the potential means of ameliorating any negative consequences of this impact.

Regardless, the analysis above demonstrates that an Ontario greenhouse model should include a crop selection of cannabis, cucumbers, peppers, and tomatoes to have an accurate representation of the crop requirements that greenhouse growers are most likely to address within the province. Within the model, the choice of crop was a string user-input from a front-end drop-down menu, and from there, the model read from the data tables the lighting, watering, temperature, and other like requirements for the plant; the crop selected by the user is consequently left with a considerable effect onto the output of the code.

Concerning the data storage of crop choices, there are two spreadsheets read through by the code, given and described as follows:

- Crop Light: Contains lighting information for crops including the required DLI, photoperiod lengths, and PPFDs accompanying both.
- Crop Data: Contains mainly temperature and humidity data, with lighting data omitted.

Note that these excel datasheets are available in Appendix A, linking to the GitHub repository with the named spreadsheets available.

In a future iteration of the code, it may be prudent to combine the crop data into one spreadsheet; they were seperated due to the formats being different, causing iteration through each sheet to be more difficult combined than if they were separate.

Crop Selection as an Input

Though crop choice is only used as an input to several functions, it is still important to note the research and data accompanying the crops.

Next Steps

The four vegetable crop choices for Ontario may be representative of Ontario's most popular crops but there is opportunity to include other potential crops such as apples, berries, grapes, etc. The benefit from including these crops is increased applicability, though the requirements of growing fruits and vegetables may not vary significantly per crop [15]. This step is likely to be a work intensive one, necessitating the acquisition of the crop's required DLI, water, spacing, and other important parameters for full model functionality.

3. Lighting

Research and Data

To incorporate a means of reducing the overall electricity consumption of a greenhouse's lighting selection, exhaustive research was performed and several simplifying assumptions had to be made, as described later in

The first simplifying assumption made with the lighting was concerning the ambient light received by the greenhouse, which varies considerably based upon location. As it was decided that utilizing multiple locations within Ontario would be too work intensive for the four month time constraint of this project, possible locations were scoped down to Leamington, Ontario. The municipality of Leamington is within the region of Essex and is within proximal distance to the Chatham-Kent region, making Leamington an optimal representation of the two areas where the majority of Ontario's greenhouses are located [4]. Therefore, the municipality of Leamington is an ideal location to include within the model concerning greenhouse placement in Ontario, though other locations would extend the model's application to other cities and ought to be considered for future iterations.

The ambient solar data for Leamington could not be found online and consequently, ambient solar data from the year 2010 in the city of Detroit was utilized to represent the annual ambient solar data expected for Leamington, Ontario. Detroit was chosen because it was roughly 60 km North-West of Leamington; a distance close enough such that it could be assumed the solar insolation did not vary considerably. The 2010 data was the most recent solar insolation data available for the city of Detroit, from the National Solar Radiation Database and the metric used was the METSTAT Global Solar Radiation that reached the point of reference (the Detroit Metropolitan Airport) [16]. Canadian weather databases were considered but due to difficulties in opening the encrypted files or hourly annual solar profiles not being available, the Detroit database was used [16], [17]. The Global Solar Radiation (Wh/m^2) had to be converted to photosynthetic photon flux density (PPFD) of the incoming solar radiation to compare it to the lighting requirements of the plants based upon the lighting fixture selection function as described in the following paragraph. The equation outlined below was used to convert the incoming solar radiation to PPFD (micromoles/m^2/s):

$$PPFD = Solar\ Radiation * 4.57 * 0.45 * 10^6$$ [18]

In this equation, the solar radiation (Wh/m^2) is converted to PPFD (micromoles/s/m^2). By multiplying by 4.57 and 0.45, the energy of the sunlight is converted to photons (one J ~ 4.57 moles of photons) and the fraction of solar radiation that is absorbed by the plants (the photosynthetic fraction of 400-700 nm wavelength, or roughly 40-50% of solar radiation) are obtained respectively [18]. Note that to convert Wh to Micromoles/m^2/s, multiplying and dividing by the value of 3600 cancels out to one and therefore it was not included in the above equation.

The data for lighting is compiled into four spreadsheets, outlined below:

- Ambient Light (Detroit)
- Lighting Selection datasheet
- Crop Lighting Requirements
- Ambient Light 24 hour profile

Note that these spreadsheets are found in Appendix A, where the link to the GitHub repository is available.

Algorithm

The lighting selection algorithm was based upon the principle of minimizing the required electricity consumption of the lights used, and in the research performed for this project, the only comprehensive lighting list that included lighting fixture price, type, and electrical input was in a 2014 published study on the subject by Nelson and Bugbee [19]. Please refer to the table of lighting choices in the GitHub repository from Appendix A.

The lighting selection algorithm works as follows, the DLI (moles/day) required by the plant is converted to PPFD using the user's input crop choice and photoperiod for the plant as per the equation below.
$PPFD = (DLI * photoperiod)/3600/10^6$ [10]

With the PPFD required by the selected crop calculated, the lighting choice that meets the PPFD requirement using the lowest number of fixtures (multiple fixtures may be needed to satisfy the PPFD of one crop), the total electricity consumption from each possible lighting choice is determined and the selection with the lowest required electrical input (J) is selected as per the equation below.

$$Lighting\ Consumption\ (J) = Total\ \#\ Lights/Plant * Plant\ Number * Electrical\ Consumption/\ Light$$

After selecting the optimal lighting choice based upon minimal electricity consumption, other valid outputs are calculated. The lighting cost for operation in Ontario is calculated using the Time of Use (TOU) rates (The TOU spreadsheet as well as other datasets used to develop this model is hosted on the GitHub repository. Please see Appendix A for the GitHub link) based upon the user input photoperiod (start and end times for the lighting of the crops). As for ambient lighting, the incoming solar radiation from Detroit (converted to PPFD) is compared on an hourly basis to the PPFD requirements of the user-selected crop. Should the incoming solar radiation, accounting for the transmissivity of the greenhouse, be greater than the PPFD required by the plant based upon its photoperiod, then the user may shut off the lights strategically to save energy. The amount of energy that may be saved, returned in kWh, is subsequently given.

The purpose of the lighting module is not only to select a lighting choice based upon minimizing electricity input but also to return the cost of operating the lighting throughout the year and the expected electricity savings should the lighting be turned off strategically when ambient lighting is sufficient to meet crop requirements.

Inputs and Outputs

For the lighting module, multiple functions are utilized to obtain the lighting selection, electrical consumption and cost, and the potential for savings. These functions, in the chronological order of which they will be called, are given below with their inputs and outputs. A high-level description of this module's relatively complex functionality when compared to other modules is given above.

Function 1 - Greenhouse Transmissivity:

- Inputs:
  - Excel datasheet of material transmissivities from virtual grower
  - User-selected string of material comprising the greenhouse "window" (the "window" is elaborated upon in the Next Steps section for lighting).
- Outputs:
  - Transmissivity (expressed as a decimal) of the greenhouse.

Function 2 - Ambient Light Received:

- Inputs:
  - Transmissivity returned from Function 1
  - Representative 24 hour profile of sunlight reaching
- Outputs:
  - An array of the ambient sunlight PPFD reaching the greenhouse (size of 12x24 with 12 representing the month and 24 representing the hours in each representative day in a month). Note that each value in the array has been multiplied by the transmissivity input into the function.
  - Value of maximum PPFD reaching greenhouse (Micromoles/m^2/s)
  - Value of average PPFD reaching the greenhouse (not used in later functions, currently output for user's information).

Function 3 - Deficiency of Light:

- Inputs:
  - Excel datasheet of crop lighting requirements
  - PPFD array returned by Function 2
  - User selected crop choice (string)
  - User selected crop photoperiod (h)
- Outputs:
  - Minimum PPFD required by the crop and maximum PPFD required by the crop (Micromoles/m^2/s)

Function 4: Lighting Selection Algorithm:

- Inputs:
  - Excel datasheet of possible lighting choices
  - Minimum PPFD required by the crop (returned from Function 4)

    - Maximum PPFD required by the crop (returned from Function 4)
    - User-input photoperiod (h)
    - Plant number in greenhouse (returned from function described in Water Consumption module)
- Outputs:
    - Lighting recommendation (as a string displayed for user)
    - Number of fixtures required to adequately light all of the plants in the greenhouse
    - Total upfront cost of purchasing all lighting fixtures ($)
    - Hourly electricity consumption (kWh) of all the lighting units combined

Function 5: TOU Price of Lighting in Ontario:

- Inputs:
    - User input start and end time (24 hour clock) for the crop lighting schedule
    - TOU excel spreadsheet for Ontario's electricity fees (both Summer and Winter pricing included in this sheet)
    - Hourly electricity consumption of lighting (kWh) returned from Function 4
    - User-selected photoperiod length (h)
- Outputs:
    - Summer and winter electricity cost of lighting in ($)
    - Annual electricity cost of lighting in ($)
    - Electricity consumed in a year (kWh)
    - None if and only if user input start and end times do not match the photoperiod selected by the user (i.e. the user's input is not consistent)

Function 6: Electricity Savings from Strategic Light Outages Based on Ambient Conditions:

- Inputs:
    - Spreadsheet of detroit solar insolation reaching the Earth (hourly data and PPFD calculated)
    - Minimum required crop PPFD returned by Function 3
    - Transmissivity returned by Function 1
    - Electricity consumption of lighting in kWh returned by Function 4
- Outputs:
    - Potential annual energy savings (kWh) if lighting is strategically shut off when the ambient solar is enough to meet crop needs, accounting for transmissivity limitations.

Though this module is functional, it may still be subject to improvement, as detailed in the subsection below.

Assumptions

Absence of Heating and Light Shadow from Fixtures

Assumptions were made concerning the operation of the lighting fixtures, including the absence of heating provided by the lighting fixtures and the shadow that the lighting fixtures provide over the plants in the current model. The heating of the lighting fixtures may lower the heating required by the greenhouse and the shadows cast by the lighting may lower their ability to provide the crops with the required light, meaning that there is opportunity to improve the current iteration by including such information, though the research may be a work intensive process.

Transmissivity "Window" Approximation

The transmissivity is currently assumed to come solely from a "window" representative of the entire greenhouse, which is to say that the transmissivity of the entire greenhouse is approximated from one material used to make the windows. In reality, the transmissivity of a greenhouse is a function of all the materials comprising the structure and their respective transmissivities.

2014 Lighting Selection List is Representative of Current Technology

Technology innovation since 2014 has likely rendered the 2014 list of lighting used in the lighting selection function as out-of-date somewhat. However, as this was the only exhaustive list of lighting found, it was assumed that the lighting list was representative of current technology despite the years since publication.

Next Steps

Due to the omitted complexity of the multiple transmissivities, their interactions with ambient sunlight, and the positioning of this sunlight over the crops, it was decided that accounting for all this information might over complicate the model, risking the coding becoming bogged down with the transmissivity module. To prevent transmissivity from becoming a timesink in the four month design schedule, this simplifying assumption was made to consider only the materials making up the greenhouse's windows. In future iterations of this software, it is not clear how much taking into account all transmissivities will alter the model's outputs, since transmissivity influences the ambient PPFD received by the plants and therefore, a future team may choose to account for the complex effects of transmissivity.

Electrical lighting specifically, in its current form, is functional but improvements may still be made. The most pertinent change is the list of lighting options, which is taken from a 2014 economic analysis on available lighting choices within a greenhouse by Bugbee and Benson. As pointed out during the April 23, 2020 presentation by a Virtual Grower representative, even the relatively recent list provided in the analysis is outdated due to the technological innovations in lighting since 2014. Therefore, a more up-to-date list should be compiled for the data to read from, likely requiring lengthy research from lighting fixture datasheets. Such a list would require information such as the electrical input (J or Wh) of the light, the fixture cost, and the PPFD or PPF (with area of emittance) at a minimum, with other information such as photon output and efficiency being optional.

Finally, the current iteration of the model only offers lighting selection based upon the minimal electrical input required by the lights, which accomplishes the objective of minimizing electricity demand from lighting but may contradict the desires of growers when it comes to balancing upfront cost and other valid parameters. To elaborate, if a lighting fixture has a low electricity input and a high upfront cost, then a grower may be drawn away from it in favour of a lighting selection that balances electricity input and upfront cost. Therefore, the user should be able to input their preferences, specifying a maximum upfront cost or a preferred lighting type to the front-end to allow for a more user-defined output, without sacrificing the module's objective of minimizing electricity demand for greenhouse lighting.

4. Water Consumption

Research and Data

This module is not highly relevant to the energy consumption of a greenhouse but is key to its operation would be the water requirements of each crop. Currently, the water requirements of each crop, assuming traditional watering (methods like drip irrigation were not accounted for) were used to determine the daily watering needs of all crops and the metered water cost for greenhouses used in Leamington, Ontario were applied to find the daily cost of watering the crops [20]. The IESO states in its posterity report that alternating watering methods has little impact on energy savings, with an example being switching from traditional watering to drip irrigation being estimated to save only 3% of the energy required by a greenhouse annually [4]. Regardless, users should be informed of the water requirements of the crops as it is relevant to the operation of the greenhouse, necessitating its inclusion into the model.

The data concerning water consumption is contained within one spreadsheet, namely the Water Consumption spreadsheet. Please refer to Appendix A for the GitHub repository containing this spreadsheet.

Inputs and Outputs

The inputs and outputs for the water consumption function are as follows:

- Inputs:
    - Area of greenhouse in m^2 (returned by the area calculation function described in Greenhouse Structure section)
    - Plant choice as a user-selected string from the drop-down menu in the front-end interface
    - The aforementioned spreadsheet containing crop watering requirements

- Outputs:
    - Number of plants in greenhouse
    - Minimum and maximum costs of watering these plants on a daily basis ($), based on watering requirements of selected crop
    - Minimum and maximum daily crop water consumption range in litres based upon the watering requirements of the selected crop

Assumptions

Traditional Watering is Used Only

Traditional watering is assumed, limiting the watering methods available to the user. It is also assumed that the water is not reused when watering crops, and that rainwater is not used.

Next Steps

As water consumption is not highly relevant to the energy consumption of a greenhouse, adding to this portion of the model may not be as important as other modules. However, to increase the applicability of the software, the water costs of other municipalities might be integrated into the model, allowing the user to select from a drop-down menu in the user interface to provide other possible costs for greenhouse watering. Additionally, though the energy savings of drip irrigation are minimal, it could also be integrated into the model as a choice for the user, whether they would prefer a method of drip irrigation over traditional watering.

5. Heating

Research and Data

The purpose of heating in a greenhouse is to artificially maintain the ideal growing conditions at all times, regardless of external variations. Heating calculations require consideration of ambient conditions, as the heat loss needing to be replaced by using fuel depends on several external factors. The data required for heating calculations includes the following:

- Ambient temperature data (C)
- Ambient wind speed (m/s)
- Ambient solar radiation (W/m^2)
- Fuel types with their respective energy and efficiency values
- Material properties for walls and energy curtains (U, i)

Ambient temperature and wind speed data was obtained from the Government of Canada databases for Chatham meteorology station [21]. Solar radiation was drawn from the Detroit profile used for lighting calculations in the model, discussed in the previous sections. Information on fuel types and material properties was primarily drawn from the Virtual Grower database [7].

Inputs and Outputs

- Inputs
    - Selected fuel type
    - Material and energy curtain selection
    - Ambient conditions from data

- Outputs:
    - Daily heating energy demand profile
    - Heating costs ($)
    - Fuel consumption

Algorithm

The heating requirements of the greenhouse includes two components: temperature adjustments and compensation for heat loss. These were determined using the following methods:

Internal Temperature Adjustment:

If, based on the optimal temperature schedule for a selected crop, a temperature increase is required, the surplus heating required, the surplus energy required to achieve the change is supplied in the hour immediately preceding the change. This is calculated using the following formula:

$Q = mC\Delta T = (\text{volume of Greenhouse} \times \text{density of air}) \times (\text{specific heat capacity of air}) \times (T_{\text{next hour}} - T_{\text{current}})$

Heat Exchange:

Heat is exchanged with the external environment through the following three mechanisms:

Conduction: $Q = \text{area } (m^2) * U * (\text{Wind speed correction factor}) * (T_{\text{ambient}} - T_{\text{internal}})$

where U is the heat transfer coefficient, and the wind speed correction factor modifies it to account for changing ambient wind speeds

Convection: $Q = \text{volume } (m^3) * i * (\text{Wind speed correction factor}) * (T_{\text{ambient}} - T_{\text{internal}})$

where i is the air infiltration coefficient, and the wind speed correction factor modifies it to account for changing ambient wind speeds

Radiation: $Q = \text{solar insolation } (W/m^2) * \text{area} * \text{heating factor}$

where the heating factor is an aggregated coefficient to determine the amount of solar radiation being captured for heat (default set to 0.33 [7])

Radiation includes only solar heating, as the magnitude of radiative heat loss is insignificant compared to the other mechanisms.

Total: $Q_{\text{total}} = \text{Internal Temp. Adjustment} + \text{Loss}_{\text{conv}} + \text{Loss}_{\text{cond}} - \text{Gain}_{\text{radiation}}$

Using these calculations, the heating energy requirement for each hour is obtained.

Assumptions

Heater Output is Always Constant with Given Amount of Fuel

A major assumption with the heating module is the lack of consideration of the heater equipment. The calculations do consider a heating efficiency based on fuel type, attributing a small portion of the potential energy use to be lost through inefficiencies. However this method still assumes a universally consistent heater, where energy output is a simple linear function of fuel consumption. In practical applications, heaters require ramp-up meaning that consistent adjustments of output may result in inefficiencies. In addition, these units would also have slightly different efficiencies depending on the exact output needed.

Greenhouse is Treated as a Flat Surface

The area of the greenhouse is used to determine the amount of solar radiation entering the system. This is a simplification, as it assumes no vertical profile for the greenhouse, and assumes all radiation is normal to the ground. This assumption is made to simplify the solar heating calculations, as factoring in the radiation obtained through the walls of a tall greenhouse would notably complicate the process with relatively little incremental improvement.

33% of Solar Radiation goes into Heating

This value was reached by assuming that 33% of the incoming energy is reflected off the greenhouse, and 50% of the energy that enters the greenhouse is taken up by the plants for photosynthesis. This leaves 33% of total energy available for heating. These numbers were drawn from Virtual Grower's built-in assumptions, deemed a credible source for the model [7].

No Energy Needed to Cool

While heating is a significant issue for greenhouses in Canadian winters, greenhouses can overheat, requiring cooling solutions. These typically involve fans that circulate the hot internal air with the slightly cooler external air [22]. The model showed several hours during summer months when the internal temperatures were significant enough to turn off the heating, however if the external temperatures range too high then chillers may be necessary.

Heating from Lights

The two main light choices, LEDs and HPS lights, differ significantly in terms of upfront cost and energy consumption. As discussed previously, the high energy consumption of HPS lights is a disadvantage for efficient electrical lighting, the HPS lights. However the HPS lights radiate notable amounts of heat as well, which can help off-set the heating fuel requirements. The heating from lights was not factored into the model, which attributes an unfair advantage to LED lights for selection.

Design Decisions

Representative Profile

In order to determine the heat loss and solar gain, ambient weather conditions are required. Specifically, temperature, wind speed, and hourly insolation all contribute to the energy exchange between a greenhouse and its surroundings. Representative data was needed in order to simulate weather conditions. As opposed to offering users a choice to select their greenhouse location, the location for ambient conditions was set to Southwestern Ontario, in the Leamington-Kingsville-Essex region. The most significant growth in the greenhouse industry is observed in this region, and ambient data was available at the required granularity from nearby Detroit and Chatham.

Representative profiles, one day for each month of the year, were constructed using the 50th percentile of each hour for the given month. The 50th percentile was selected since the profiles were needed to contribute to aggregate values, and over the course of the year it is assumed that deviations from the 50th percentile mostly cancel out. The choice of representative profile does not contribute to significant localized decisions, and therefore the impact of the specific data used is levelled out with aggregation of all days to achieve annual heating results.

Scoping Out Moisture from Plants

All air heating calculations are performed assuming dry air, and changes in humidity are not tracked. This assumption becomes impactful as the crops output significant amounts of moisture into the air during photorespiration, which allows the air to capture more energy. Scoping out humidity calculations was necessary due to the limited timeframe, and limited expertise of the design team in this area. Modelling plant behaviour is extremely complex, and would require extensive research. While assuming no changes in humidity does reduce the validity of the results, it was determined to be an acceptable trade-off in order to simplify the release of the initial model.

Next Steps

Heating from Lights

As previously discussed in the report, heating impacts of light fixtures were not included in the model. This is a notable area for improvement, as the built-in assumption inherently disadvantages HPS lights. The radiated heat from the various lighting options should be researched and appropriately modelled in order to make the selection decision more fair, and the model more accurate.

Ambient Heat Loss and Gain

In order to determine heat loss through conduction and convection, a wall material and energy curtains are selected by the user. The loss calculations are impacted by these material parameters, however a more detailed analysis of the combined impacts of walls and curtains is needed. In the current model, energy curtains are only factored in for convective losses, as they are primarily designed to reduce those [23]. However conductive losses are impacted as well, and this behaviour was not yet modeled to reduce model complexity at the initial stage.

For solar radiation, in addition to more detailed analysis of radiation captured by the 3-dimensional greenhouse structure, further improvements should be made to researching

Cooling

As noted in the assumptions, cooling needs were not considered for the initial model. Further research into the potential cooling needs of the greenhouses should be conducted in order to effectively quantify the impact, and if deemed significant, incorporate it into the model.

6. Storage

Research and Data

In order to evaluate the impact of energy storage technologies on greenhouse electricity demand, the parameters and features of various energy storage technologies must be evaluated. Sabihuddin et al., at the University of Edinburgh, conducted a thorough review of various energy storage devices across four categories, namely: mechanical, chemical, electromagnetic, and thermal storage. This paper compared these technologies on the basis of specific energy/power, efficiency, lifespan, cycle life, self-discharge rates, capital energy/power costs, etc, and thus creates a foundation upon which the addition of storage systems can be modelled [24].

Inputs and Outputs

Modelling the impacts of energy storage requires several inputs, detailed below. All aside from the storage characteristics and the energy profile are direct user inputs.

- Inputs
    - Storage mode (cost or profile optimization)
    - Storage technology option
    - Max power capacity
    - Max energy capacity
    - Storage characteristics (from data)
        - Efficiency
        - Depth of discharge
    - Pre-storage electricity profile (from previous modules)

The primary output of the storage module is used to demonstrate the impact of incorporating energy storage on the electricity consumption patterns of the greenhouse.

- Outputs
    - Storage use profile
    - New hourly electricity profiles
    - Monthly cost savings due to storage

Algorithm

There are two modes of energy storage operation built in; cost optimization and profile flattening. Storage power and energy capacities are required for both methodologies. Efficiency is incorporated by applying the following formula to all charges:

$E_{discharge} = (E_{charge}) / (efficiency)$

Depth of discharge, expressed as a percent of total capacity, describes the degree to which a storage unit should be depleted during general use. Is factored in as shown below:

$E_{effective} = (E_{user\ input}) \times (Depth\ of\ discharge)$

Cost Optimization

Cost optimization leverages the Ontario TOU electricity pricing and utilizes the storage unit to charge when prices are low, and discharge when prices are high. The algorithm is described below.

For a 24hr profile:

1. Sort all hours in terms of discharge priority
    a. Price (highest to lowest)
    b. Consumption (highest to lowest)
2. Set:
    a. $h_{discharge}$: first hour on the list
    b. h_{charge}: last hour on the list
3. Determine if charge-discharge pairing (h_{charge}, $h_{discharge}$) is feasible:
    a. Storage power capacity is not exceeded at either hour
    b. Storage energy capacity is not exceeded at either charge or discharge period
    c. Storage has sufficient charging between discharge periods, and sufficient discharge between charge periods
    d. Objective value (total electricity cost) is improved by the change
4. If feasible, increment the new profile by:
    a. (+1/efficiency) at h_{charge}
    b. -1 at $h_{discharge}$
5. Else:
    a. Set:
        i. $h_{discharge}$: next hour on the list
    b. Once all pairings with h_{charge} have been evaluated:
        i. h_{charge}: next hour on the list from reverse order
    c. Repeat from Step 3
6. Iterations continue until:
    a. No feasible charge-discharge pairings found

Profile Flattening

Energy storage is often used to shave the peaks off load profiles by discharging at the points where the profile of use is the highest. The maximum amount of power drawn from the grid is thus reduced, which provides several benefits. These included reduced grid connection costs, and a lower overall power rating needed for equipment. The algorithm for the profile-flattening storage method is described below.

For a 24hr profile:

1. Sort all hours in terms of discharge priority
    a. Consumption (highest to lowest)
2. Set:
    a. $h_{discharge}$: first hour on the list
    b. h_{charge}: last hour on the list

3. Determine if charge-discharge pairing (h_{charge}, $h_{discharge}$) is feasible:
    a. Storage power capacity is not exceeded at either hour
    b. Storage energy capacity is not exceeded at either charge or discharge period
    c. Storage has sufficient charging between discharge periods, and sufficient discharge between charge periods
    d. Post increment, the new load at h_{charge} does not exceed the initial load at $h_{discharge}$
4. If feasible, increment the new profile by:
    a. (+1/efficiency) at h_{charge}
    b. -1 at $h_{discharge}$
5. Else:
    a. Set:
        i. $h_{discharge}$: next hour on the list
    b. Once all pairings with h_{charge} have been evaluated:
        i. h_{charge}: next hour on the list from reverse order
    c. Repeat from Step 3
6. Iterations continue until:
    a. No feasible charge-discharge pairings found

Assumptions

User Knowledge

The requirement that users input storage capacity imposes an assumption that the end-user is aware of the storage options available to them on the market. This assumption can be considered valid, as the user can do research, contact storage companies for quotes, or even hire a consultant to determine the power and energy capacities of market units.

Optimal Storage Schedule

A notable assumption with the storage module is that storage is deployed optimally by the user. This requires that the storage system be programmed with a control system using the same algorithms described above, or that the user sets the schedule completely ahead of time.

Design Decisions

User sets max capacity and energy

The storage inputs required to run the model include a clear power and energy capacity for the storage unit. This decision was made weighing the validity with the outputs with simplicity of use. The primary alternative to this decision is limiting user inputs to the type of storage and a maximum budget they have to spend on it. Using these parameters, and aggregated market research to estimate the cost per capacity of the storage option, the model would determine an estimate for the capacity attainable with the set inputs. While this method simplifies user experience, the added layers of uncertainty and assumptions introduced greatly diminish the validity of the storage outputs. In this case, the tradeoff in model performance was not significant enough to warrant selecting this alternative method.

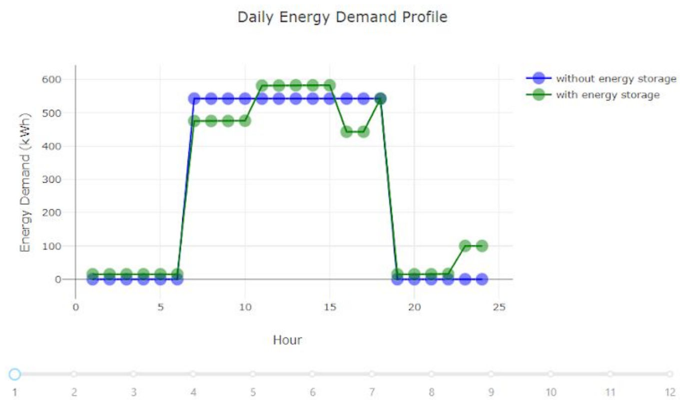

Figure 6. Comparison of Profile With and Without Storage

Comparison of Profiles

The model always requires the user to set preferred parameters for storage, displaying the profiles and peaks with and without storage on the same plots (Figure 6). This decision allows the user to see the clear impacts of the storage option in addition to the single annualized saving value presented on the interface. By providing the storage-modified, the decision support tool becomes more versatile for use by system planners, who can extend the outputs to aggregate them for system-level impacts of large-scale adoption of storage in Ontario greenhouses.

Selection of Storage Options

Several storage technologies were researched during the creation of the model. These can be seen in the data files associated with the model. However, for the completed mode, only 5 technologies were included as options for a user to select. This limitation was imposed to make the display less overwhelming with over 20 choices, and instead constrain them the technologies deemed most valid. This selection process was primarily based on maturity of the technology, as well as its availability on the market for commercial use.

Next Steps

Custom Storage Plan

A worthwhile extension could be providing users the option to customize their storage plans. This feature could be beneficial for incorporating other considerations into the optimization, such as incentives from the IESO to reduce load at specific hours, or more intricate optimizations between the heating and lighting systems.

7. Electricity Consumption

Based on the lighting profile, as well as that of heating if the fuel type is electricity, the total electricity profile can be determined. A main reason to perform detailed analysis on the electricity consumption patterns is to quantify the burden that the greenhouses place on the electrical grid. The objective through the decision support tool is to show this burden with the varying parameters that users can control. This component strongly considers the needs of both groups of primary users; greenhouse owners and electrical system planners.

Design Decisions

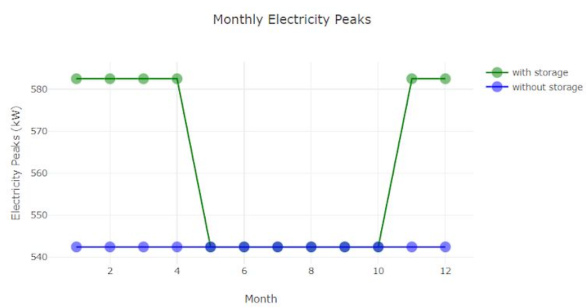

Figure 7. Monthly Electricity Peaks With and Without Storage Option

Display of Monthly Peaks

The electrical infrastructure required to connect greenhouses to the electrical grid need to have sufficiently high power ratings to meet the greenhouse needs at the highest usage points. For this reason, all monthly peaks are displayed in order for the users to be able to ascertain the highest power requirements (Figure 7). If only lighting is accounted for in the electricity consumption, the monthly peaks will show little to no variation, however if heating is also electric, this plot offers greater insights. Energy use is also reported as a single value across the year, as energy does not have the same peaky nature as power due to it being a measure over time.

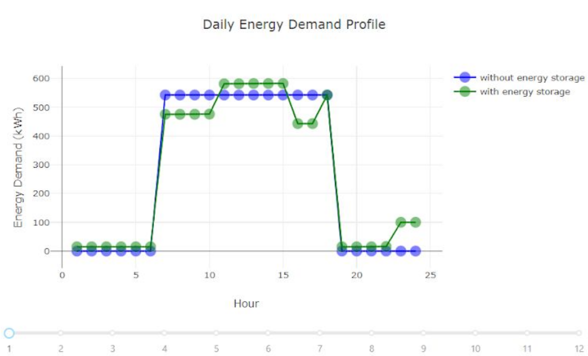

Figure 8. Daily Electricity Profile With and Without Storage Optimizing for Cost

Display of Daily Profiles

In addition to displaying monthly peaks, daily profiles are also of interest to planners and growers if they want to improve their electricity use. Observing the profiles can shed light on areas for efficiencies through storage or slight changes to the photoperiod. As shown in Figure 8, The plot contains a slider feature so that the user can vary the month being shown, which can provide more through information on seasonal variation. Similarly to the plot of peaks, the impact of storage is clearly shown on the plots in order to highlight the potential value, or lack thereof, of investing in energy storage to make the greenhouse load profiles more agreeable to the system.

8. GHG Emissions Modelling

Research and Data

GHG emissions were modelled in order to help growers understand the impacts of their decisions, and to enable them to make more sustainable choices. GHG emissions are reported as the amount of carbon dioxide equivalent released in a given period of time (g CO_2-e/yr). CO_2-e is a measure of Global Warming Potential (GWP) which is usually expressed over a period of 100 years. GWP evaluates the global warming impact of various gases using CO_2 (with a GWP of 1) as a reference. Other greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) respectively have GWPs of 36 and 298 times that of CO_2 [25].

The data required for determining gCO_2e for each scenario is restricted to the emission factors. Using [26], a mass of CO_2e is obtained per unit energy gained from the fuel type for the burning of fossil fuels for heating. To account for the emissions of the electricity consumed by the greenhouse, the provincial grid intensity is utilized. This value captures an approximation of the cost, in terms of gCO_2e, of delivering 1 unit of electricity from the grid [27].

Inputs and Outputs

The main input factor impacting emissions of the greenhouse is the fuel type selected. Other parameters influence emissions indirectly by feeding into t total energy requirements to maintain optimal conditions.

Emissions are captured in two ways within the model outputs. The first is as a total annual value of gCO_2e emitted per year. The

Assumptions

Independence of Grid Intensity and TOU
The grid intensity used to calculate the emissions cost of electricity did not vary with the time that the electricity is drawn from the grid. Throughout any day, the Ontario grid varies the generators that are deployed, and during certain times, such as peaking hours, leans more heavily on burning natural gas than base loads at night. The argument to disregard this time-variance of the grid intensity is that an individual greenhouse is too small to actually impact the generator dispatch, and therefore the scheduling of the greenhouse consumptions patterns does not significantly impact generators being actively deployed at the time of use, or the amount of power that those generators need to generate onto the grid.

No variation based on heater type

Since different heater types were not explicitly modelled in the current release of the project, an assumption is introduced that the emission calculation due to heating is purely a linear function of fuel type and heating energy required. This assumption is sufficient to provide a rough estimation of the consequences of fuel choices, however more detailed modelling involving heater systems would yield more accurate results.

Design Decisions

Displaying Monthly GHGs

As the GHG emissions vary based on heating needs, it was pertinent to include a progression of emissions throughout the months of the year. The users likely would not adjust energy consumptions practices throughout the year, as the purpose of the greenhouse is to create an artificial environment for year-round growing, the impact of seasonal variation can help highlight the disadvantages and inefficiencies of growing warm-climate crops in Canada.

Next Steps

Accounting for Grid Intensity TOU

It is reasonable to argue that drawing power at off-grid times is more emissions-effective for the province, and the numbers become more convincing as the electrical load level of the greenhouses is scaled up. When looking at several greenhouses being aggregated together, the overall electrical load would likely be significant enough to impact the generation dispatch of the grid. If a more accurate emission model is desired, it would be worthwhile for future developers to build functionality that can consider the differences between generator mixes during different times throughout the representative days

9. Cost Modelling

Inclusion of cost calculations was deemed necessary as all business decisions for commercial operations are made with a strong consideration for the financial implications. Initial goals of the model included a detailed cost breakdown to assist users in making financially sound decisions for new greenhouses as well as retrofits of existing units. The final model is significantly more limited in scope, primarily due to the complexities of modelling the many costs of commercial greenhouses with a level of precision deemed acceptable.

Design Decisions

Removal of Overall Cost Estimate

The primary justification for removing an overall CapEx cost from the list of outputs is that the model would need to make several generalized assumptions to reach a final value, and growers aren't likely to make business decisions based on such over-simplified calculations. In most cases, trained professionals would be paid to complete detailed cost analysis, rendering cost outputs of the model redundant and greatly inferior.

Lighting Costs

Lighting is a very significant component of greenhouse operations, contributing the bulk of electricity use and often requiring significant upfront investment. The two types of lights most prevalent in the Ontario greenhouse industry are HPS and LEDs, which have notably different costs associated with them. Cost is often cited as an important decision factor for growers to use HPS over the more efficient LEDs, and therefore it was deemed necessary to showcase the numerical tradeoffs that are incurred with the vastly different costs of the different lighting types.

Next Steps

Upfront Cost for Storage and Materials

While upfront costs for light fixtures were included, storage and materials expenses were left out of the model. This was done as the uncertainties of the cost calculations of these two are much greater, as they cannot be broken down to units as simply as lighting fixtures. This issue is especially prevalent in the case of storage, where the user specifies the size of the storage system by power and energy capacity, however no clear methodology was found to obtain a CapEx cost for the storage unit with an acceptable degree of precision. Accounting for the upfront costs of both of these elements would provide notable value to the users, as both storage and energy curtains can be added on as retrofits, therefore they would need to determine the investment required for such additions, as well as the benefits they provide.

Next Steps of Model Development

Software Design

Extendibility is one of the core design values in this project. Often in software design, having modularized algorithms can allow the users to understand the algorithms more easily, which is one aspect that this project can improve on. More modularized algorithms that link to modularized visualisation can also have faster simulation runtime. In addition, proper coding practices can enhance the professionalism of this model, such as incorporating Python PEP8 commenting style and making use of git version control. In terms of frontend design, more user interactivity can be implemented to give users more control of what they would like to explore in greenhouse modelling.

Sensitivity Analysis

Two types of sensitivity analyses were discussed throughout the duration of the project: sensitivity with respect to parameter data, and sensitivity with respect to user inputs.

Most of the data utilized in the model does not come from single, empirically determined values. Data is typically obtained from a canvas of the available literature, and stored as a range of feasible values. In order to factor in the uncertainty of the parameter values within a set range, a Monte Carlo simulation can be included. Monte Carlo simulations are a common technique for understanding risk or uncertainty [28]. In the case of the decision support tool, the simulations would be run a high number of times, with iterations running through different combinations of possible data values, within the permitted ranges. Through statistical sampling, conclusions can be drawn about impacts of the data uncertainty as it ties into the objective outputs of the model.

Understanding sensitivity with respect to specific inputs would provide the user with a clear idea of how their choice influences the objective outputs. This feature would allow the user to avoid specifying a selection for a certain input, and the model would run variations of all possible inputs in order to display comparative output plots. For example, if the user was unsure of the energy storage choices presented to them, an option could be selected which would lead to the model displaying results from runs where all other parameters are kept identical. Using this information, the user can make an informed choice about their method of on-site energy storage.

While these methods were both discussed by the team, they were ultimately scoped out of the initial release of the project due to timing constraints.

Conclusion

While the scope of the project evolved from the initial concept as described in the sections above, the main objectives set out by the team were achieved. With the simplifying assumptions described throughout this report, this tool models a greenhouse energy system and allows the user to glean insights on the electricity consumption, GHG emissions, and financial impacts of their decisions. Several areas for further development were laid out in this report, offering a new team of student developers significant opportunities to improve the model from this initial viable product.

References

[1] *Greenhouse Energy Profile Study*. IESO, 2018. Available: http://www.ieso.ca/-/media/Files/IESO/Document-Library/research/Greenhouse-Energy-Profile-Study.pdf

[2] "Targeted Call for Proposals", *IESO*, 2019. [Online]. Available: http://www.ieso.ca/en/Get-Involved/Funding-Programs/Grid-Innovation-Fund/Targeted-Call-for-Proposals. [Accessed: 31- Jan- 2020].

[3] C. Baumgardt, *Different Microgreen Genotypes Have Unique Growth and Yield Responses to Intensity of Supplemental PAR from Light-emitting Diodes during Winter Greenhouse Production in Southern Ontario, Canada*. American Society for Horticultural Science, 2020, pp. 1-8.

[4] Posterity Group, *Greenhouse Energy Profile Study*. Toronto: IESO, 2019, pp. 1-176.

[5] "Statistical Overview of the Canadian Greenhouse Vegetable Industry, 2017 - Agriculture and Agri-Food Canada (AAFC)", *Www5.agr.gc.ca*, 2017. [Online]. Available: https://www5.agr.gc.ca/eng/industry-markets-and-trade/canadian-agri-food-sector-intelligence/horticulture/horticulture-sector-reports/statistical-overview-of-the-canadian-greenhouse-vegetable-industry-2017/?id=1549048060760. [Accessed: 01- Feb- 2020].

[6] L. Schiller and M. Plinke, *The Year-Round Solar Greenhouse: How to Design and Build a Net-Zero Energy Greenhouse*. 2016, pp. 3-17.

[7] "Virtual Grower 3 Model", *USDA,* 2017. Available: www.ars.usda.gov/midwest-area/wooster-oh/application-technology-research/docs/virtual-grower-3-model/.

[8] "Dash Documentation & User Guide | Plotly", *Dash.plotly.com*, 2020. [Online]. Available: https://dash.plotly.com/. [Accessed: 28- Apr- 2020].

[9] "Dash Bootstrap Components", *Dash-bootstrap-components.opensource.faculty.ai*, 2020. [Online]. Available: https://dash-bootstrap-components.opensource.faculty.ai/. [Accessed: 28- Apr- 2020].

[10] "MechaTronix - Typical PPFD and DLI values per crop", *Horti-growlight.com*. [Online]. Available: https://www.horti-growlight.com/typical-ppfd-dli-values-per-crop .

[11] H. Bishoff and H. Burkett, *Title: The Importance of Daily Light Integral (DLI) for Indoor Cannabis Cultivation*. Smart Grow Systems, 2018, pp. 4-7.https://lumigrow.com/wp-content/uploads/2017/07/LumiGrow-LED-Growers-Guide-for-Vine-Crops.pdf

[12] "Greenhouse Structures | Ornamental Production", *Aggie-horticulture.tamu.edu*. [Online]. Available:https://aggie-horticulture.tamu.edu/ornamental/greenhouse-management/greenhouse-structures/. [Accessed: 01- Mar- 2020].

[13] K. Nemali, "Calculating Greenhouse Heating Requirements – Controlled Environment Agriculture (NEMALI Lab) - Purdue University", *Controlled Environment Agriculture (NEMALI Lab)*, 2019. [Online]. Available: htps://www.purdue.edu/hla/sites/cea/article/calculating-greenhouse-heating-requirements. [Accessed: 01- Feb- 2020].

[14] "ACF Greenhouse Surface Area Calculator", *Littlegreenhouse.com*. [Online]. Available: http://www.littlegreenhouse.com/area-calc.shtml. [Accessed: 01- Apr- 2020].

[15] "OMAFRA Crops Home Page", *Omafra.gov.on.ca*. [Online]. Available: http://www.omafra.gov.on.ca/english/crops/index.html#field. [Accessed: 27- Apr- 2020].

[16] "NSRDB Update: Site #725370", *Rredc.nrel.gov*. [Online]. Available: https://rredc.nrel.gov/solar/old_data/nsrdb/1991-2010/hourly/siteonthefly.cgi?id=725370. [Accessed: 01- Apr- 2020].

[17] "Solar resource data available for Canada | Natural Resources Canada", *Nrcan.gc.ca*. [Online]. Available: https://www.nrcan.gc.ca/energy/energy-sources-distribution/renewables/solar-photovoltaic-energy/solar-resource-data-available-canada/14390?fbclid=IwAR3U2qeVxRmgFK11a4OgmBxmTni7vghgbf1UN9jc7bHPAlkj-3z97ZD4iGk. [Accessed: 01- Apr- 2020].

[18] J. Sager and C. Mc Farlane, *Plant Growth Chamber Handbook - Chapter 1*. Iowa State University of Science and Technology, pp. 1-30.

[19] J. Nelson and B. Bugbee, "Economic Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures", *PLoS ONE*, vol. 9, no. 6, p. e99010, 2014. Available: 10.1371/journal.pone.0099010 [Accessed 1 February 2020].

[20] *Notice to Water and Wastewater Consumers*. Leamington: Municipality of Leamington, 2019, p. 1.

[21] "Hourly Data Report for April 27, 2020 - Climate - Environment and Climate Change Canada", Climate.weather.gc.ca, 2020. [Online]. Available: https://climate.weather.gc.ca/climate_data/hourly_data_e.html?hlyRange=2014-04-03%7C2020-04-27&dlyRange=2018-10-29%7C2020-04-27&mlyRange=%7C&StationID=52118&Prov=ON&urlExtension=_e.html&searchType=stnName&optLimit=yearRange&StartYear=2010&EndYear=2020&selRowPerPage=25&Line=0&searchMethod=contains&Month=4&Day=27&txtStationName=Chatham&timeframe=1&Year=2020. [Accessed: 28- Apr- 2020].

[22] A. Storey, "The 4 Best Ways to Cool a Greenhouse - Upstart University", Upstart University, 2020. [Online]. Available: https://university.upstartfarmers.com/blog/4-best-ways-cool-greenhouse. [Accessed: 28- Apr- 2020].

[23] "Energy curtains for vegetables - Greenhouse Canada", Greenhouse Canada, 2020. [Online]. Available: https://www.greenhousecanada.com/energy-curtains-for-vegetables-2791/. [Accessed: 28- Apr- 2020].

[24] S. Sabihuddin, A. Kiprakis, and M. Mueller, “A Numerical and Graphical Review of Energy Storage Technologies,” *Energies*, vol. 8, no. 1, pp. 172–216, Dec. 2014.

[25] “Understanding Global Warming Potentials,” *EPA*, 14-Feb-2017. [Online]. Available: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

[26] "Guideline for Quantification, Reporting and Verification of Greenhouse Gas Emissions", Ontario Ministry of Environment and Climate Change, 2017. Available: http://www.downloads.ene.gov.on.ca/envision/env_reg/er/documents/2017/013-1457_d_Guide.pdf

[27] “Electricity Grid Emissions Intensities by Province”, Environment and Climate Change Canada, Strategic Policy Branch, Economic Analysis Directorate, Analysis and Modelling Division, 2018. Available: https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/impact_canada/LCA-Reporting-Template-final.xlsx

[28] "The house always wins : Monte Carlo Simulation", Medium, 2020. [Online]. Available: https://towardsdatascience.com/the-house-always-wins-monte-carlo-simulation-eb82787da2a3. [Accessed: 28- Apr- 2020].

[29] A. Torres and R. Lopez, *Commercial Greenhouse Production*. Department of Horticulture and Landscape Architecture, Purdue University, 2020, pp. 2, 4-7.

[30] H. Bishoff and H. Burkett, *Title: The Importance of Daily Light Integral (DLI) for Indoor Cannabis Cultivation*. Smart Grow Systems, 2018, pp. 4-7.

Appendix A: Link to GitHub Repository

The GitHub repository for this project includes the user guide, all datasets used to develop this model and the code base.

Link to GitHub repository: https://github.com/bonnieWeng/greenhouse-modelling

Appendix B: Stakeholder Consultation

Meeting with Virtual Grower

- Electrical or thermal? - BOTH
- Could look into incorporating strawberry production
- CO_2 enrichment should maybe be a component. From a plant growth standpoint, especially in northern climates, during fall winter and spring, don't have enough ambient sunlight (that's why lighting). Add CO_2 to greatly improve crop growth (ambient ~400 to somewhere between 600-1000 ppm). If adding light, but not CO_2 , they are limiting their growth and not gettingCO_2
    - Pure injection or CO2 burner
- Greenhouse grower should be adding CO_2 , but there is pushback about using CO_2
    - Amount of CO_2 from burning fuel offsets lighting requirements
- Psychrometrics:
    - Had to halt development for several years, hiring a programmer right now to work on virtual grower. If future students look at it
        - Current evapotranspiration models/humidity models could be improved quite a bit
        - Need to get rid of enormous amounts of humidity
- Could create model in virtual grower and export to spreadsheet
- Two main consumptions:
    - Water that they evapotranspire have to be replaced
        - Penman Monteith eqns
    - Misting uses water separately for cooling
    - Would recommend going for basic estimate for first version
- Steady State Model:
    - 8760 ambient conditions, trying to maintain a particular set of parameters
    - Weather - tmyc files from NREL
- Definitely relevant, growers are asking for these kinds of decision tools
- Lots of unsolved problems, researchers are talking about it
- Use cases:
    - Wouldn't assume consultants have any particular amount of knowledge (as a former consultant haha)
    - Questions are relevant for both use cases
    - It can be difficult to consider both use cases
    - Most important choices growers have to make
        - Energy curtains
        - No lighting -> lighting
        - "With this amount of money to spend, what is the most bang for my buck"
- Did work with some local growers to do small-scale validation of the model, and part of it is that it is based on typical meteorological data
    - Ambient solar heat gain, humidity and evapotranspiration, air-exchange,

University of Toronto Growth Facilities Tour

- Peppers, cucumbers and tomatoes generally can be grown together; have similar growing conditions
- Crop diversity is important and good practice. Diversity reduces risk, ie if one crop is infected, it is less likely to spread if there is diversity
- Farmers care about yield. They will not sacrifice yield unless extrinsically motivated to do so, ie govt subsidy or some such.
  - Sub-optimal growing conditions are not used; they always aim for the optimal
- Ontario Ministry of Agriculture, Food and Rural Affairs is a good source for crop growing conditions, pest info, fertilizer info
- CO_2 atmospheric enrichment is ONLY in lab settings; not used commercially.
  - Is very very expensive
  - Using CO_2 enrichment would require a completely sealed greenhouse
  - Would majorly increase cooling costs, since you cannot ventilate using cool air from outside
  - CO_2 fertilization work best at higher temperatures ~30C; don't want to be growing crops at those high temps
- PEST CONTROL is huge; They use nematodes in the soil distributed every two weeks to kill pests
  - Much easier to manage on a preventative basis rather than post-infection control
  - Refer to : Pest Management
- Heat and light modelling is going to be very important
  - Use of single vs double paned glass
  - Use of shade blankets and shade covers
- Greenhouse conditions automatically managed by software : Greenhouse controls by Priva - reliable and futuristic
  - Humidity: Sensors measure wet bulb and dry bulb temp, calculate relative humidity from this
  - Gave us user manual for this system; looks really helpful - basically breaks down all the systems/ measurements
- Fertilization
  - One system uses irrigation system
  - Fertilizer stock is mixed into basin of water, and this is then used for fertilization
- Try to attend greenhouse growers conference for industry input
- Potential Use Case: Help growers decide is retrofit would be useful
  - From Tom: There are more use cases for retrofitting rather than building new greenhouses in Ontario.
  - Eg: Produce to cannabis: There are lots of guidelines and standards on greenhouse cannabis design, since cannabis is now regulated
  - Eg: HPS lights to LEDs
  - Eg: Glazing addition
  - Eg: Replace single-paned glass with double-paned
- There are lots of empty greenhouses in southern ontario at the moment, since it is not effective to grow crops at a very small margin
- Systems in greenhouse:

    - Heating/ cooling vents
    - Shade covers
    - Water supply
    - Sensors
    - Misting system for humidity control
    - Lighting (either HPS or LEDs)
        - LEDs are much more energy efficient + better for plants, but have higher capex
- UI seems more important now; if farmers don’t understand it, they won't bother using it
- Here's info on glass panes https://www.niagarathisweek.com/news-story/9796553-lincoln-s-red-light-district-for-plants/

Appendix C: Software Integration Notes

Front End Architecture

User Input

<table>
<tr><td>

User Input Panel

- Greenhouse structure
- Crop type
- Photoperiod
- Fuel type
- Heater type
- Lighting type
- Binary storage
- Onsite energy storage choice
- Storage objective
- Storage peak
- Storage energy

</td><td><Picture of Greenhouse Structure></td></tr>
</table>

Simulation Output

(Single valued outputs)

Annual energy consumption	**Annual water consumption**	**Annual cost**	**Annual GHG emission**

<table>
<tr><td>

(1) **Daily Electricity Demand P**

Plot Description: A line-scatter plot with 2 lines (**with** and w/o energy storage)

Add On: A slider to let the user to choose which month to present data (confirm it's doable https://dash.plotly.com/basic-callbacks)

Input: All + slider input

Output: 2 np arrays of 24-hour demand profile

Sim Output Spec: 1 df of size (24, 24). Cols 0-11 are months w/o energy storage, cols 12-23 are months with energy storage. Each row is peak demand for an hour.

</td><td>

(2) **Monthly Electricity Peak Demand**

Plot Description: A grouped histogram chart showing monthly energy peak demand for both **with** and w/o energy storage

Add On: Hover show histogram values

Input: Same as (1)

Output: 2 np arrays of monthly peak demand

Sim Output Spec: 1 df of size (12, 2). Col 0 is w/o energy storage, col 1 is with energy storage. Each row is peak demand for a month.

</td></tr>
</table>

(3) **Monthly Energy Consumption** Plot Description: A bar chart showing monthly energy consumption, grouped by the energy uses (eg. fuel, electricity grid) Add On: Hover show histogram values Input: Same as (1) - energy storage - opt. obj. Output: 2 np arrays of monthly energy consumption Sim Output Spec: 1 df of size (12, 2). Col 0 is fuel, col 1 is with electricity. Each row is energy consumption for a month. If Fuel == electricity: (use of if statement)	(4) **Monthly Electricity Cost Savings with Energy Storage Option** Plot Description: A grouped histogram chart showing monthly energy cost savings Add On: Hover show histogram values Input: Same as (1) Output: 1 np arrays of monthly cost savings Sim Output Spec: 1 df of size (12, 2). Col 0 is cost w/o energy storage, col 1 is with energy storage. Each row is energy cost for a month.
(5) **Monthly GHG Emission** Plot Description: A line-scatter plot showing monthly GHG emission Add On: Input: Output: 1 np array of monthly GHG emission Sim Output Spec: 1 df of size (12, 1). Col 0 is w/o energy storage, col 1 is with energy storage. Each row is energy consumption for a month.	(6) **Monthly Water Consumption** Plot Description: A line-scatter plot showing monthly water consumption Add On: Input: Output: 1 np array of month water consumption Plot Data Spec:

Callbacks and Backend Software Architecture Design

Decided Design decisions:

(1) Run simulation in a separate Python file (separated from the main file which mainly defines app layout and callback functions)
- Rationale: More organized and modular (avoid having 1000+ lines of codes), and therefore, easier to debug and make incremental changes

To-Be-Decided Design Decisions:

(1) Frontend- Run parallel callback functions for each graph (6 total right now) or <u>have only 1 callback function for all the graph</u>
  - Rationale for current choice (underlined): Either choice shouldn't be too hard actually because Plotly is really amazing. It allows multi-inputs and multi-outputs in the callback! However, writing codes to run parallel callback may be easier to debug and make incremental progress as a first step.
  - https://community.plotly.com/t/multiple-outputs-in-dash-now-available/19437

(2) Backend- <u>Have one single function for simulation that returns multiple outputs (each output is an instance of sim. output spec as specified above)</u> or have multiple functions for each sub part of simulation (eg. energy function returns sim. output instance (1)-(4), GHG function outputs (5), water consumption outputs (6))
  - Rationale for current choice (underlined): As a first step to make incremental progress, and then it will be decided which choice is better.

Best practice still to keep in mind when coding with Plotly Dash: If a set of outputs share different sets of inputs then it is best to separate them. Separating different sets can make the computation <u>run more efficient</u>. Conversely, if a set of outputs share the same sets of inputs, then it is best to group them together. (This is a good practice to optimize runtime on the web. However, if there is time constraint, one single simulation function may be just as good for us!)

Dash Architecture (Beta Release)

app.py
- Specify layout
- Define callback functions
 	
simulation.py
- Inputs: all user inputs
- Outputs: sim output spec
 	
figures folder
- Greenhouse structure
 	
dataset folder
- Crop data
- ect.
	simulation.py (in Dash) architecture
	import numpy as np
	import pandas as pd
	
	# Import datasets
	
	def simulation(input1, input2, input3, input4):
	  """
	  Inputs: All the user inputs as specified in the user control panel
	  Outputs: 6 dataframes, as specified sim output spec
	  Assumptions:
	  """
	
	  # simulation codes
	
	  return dataframe1, dataframe2, dataframe3

Appendix D: Project Timeline

Table D-1: Project Task List

Milestone	***Notes***
❖ Design Decision Justification	• This document will establish the first major design decision for the project • Deliverable will aid in structuring future design work
❖ Initial Stakeholder Engagement + Research	• Talking to several professors on campus for project connections • Reaching out greenhouse owners and representative organizations for input on model uses and gap addressed • Conducting research to gain an understanding of the systems and technologies involved in a greenhouse
❖ Model Prototype I	• Initial model, minimal functionality to establish structure • Goal: observe outputs with limited number of inputs
❖ Model Prototype II + Simulation	• Build all module functionality, including lighting, water use, and storage • Backend/frontend integration to allow for local hosting of frontend for presentation
❖ Presentation	• Model Prototype II ready and showcased during presentation • Final presentation to describe the model functionality and demo it
❖ Model Prototype III	• Fully functional model, all inputs and outputs are set • Proper documentation of complete design • Minor adjustments to be made to improve interpretability of outputs and code • All code organized and commented to enable future readability and model extensions

Appendix E: Background (Figures and Tables Referenced)

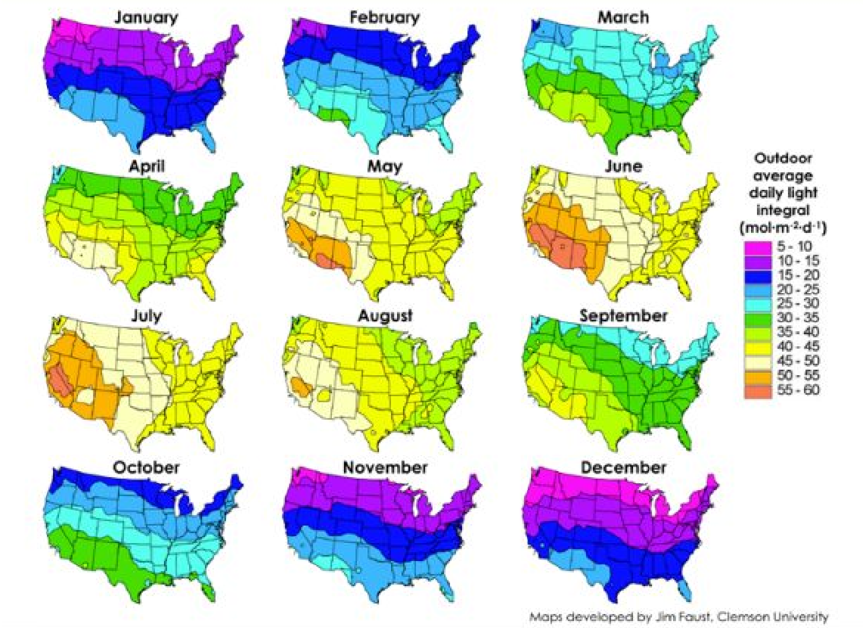

Figure E-1. American DLI [29]

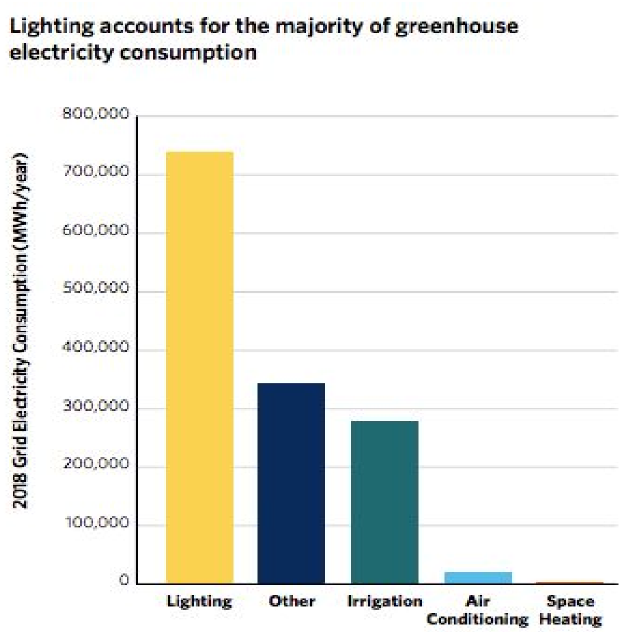

Figure E-2. 2018 Energy Use in Greenhouses [1]

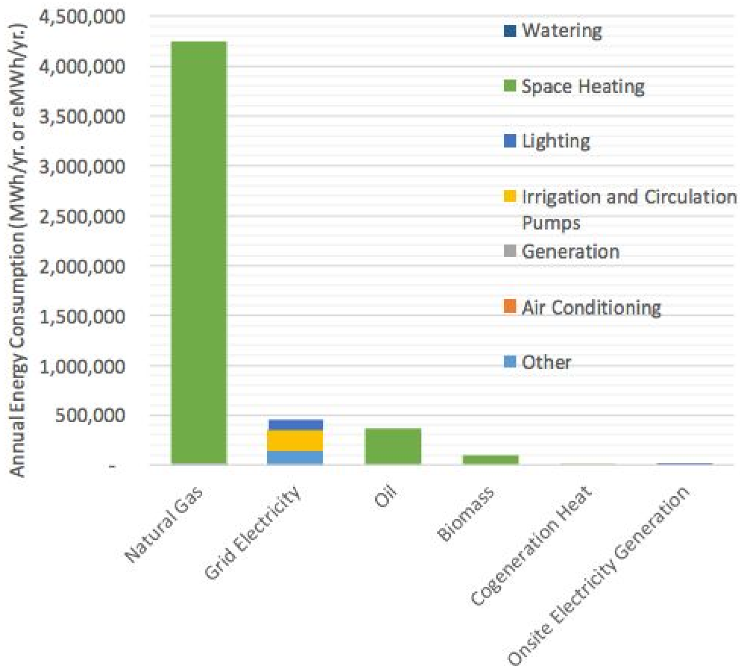

Figure E-3. Annual Energy Consumption by Source in Ontario Greenhouses

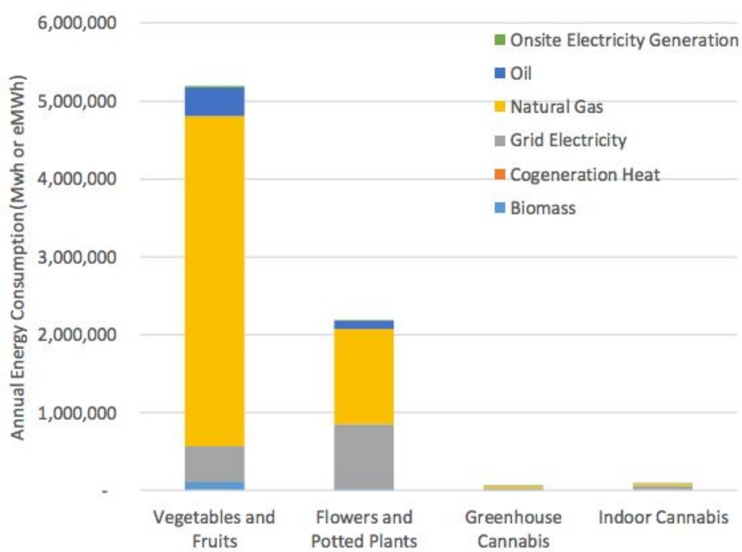

Figure E-4. Bar Chart of Annual Energy Consumption in Ontario by Greenhouse Type

Table E-1. Harvested Area of Greenhouse Vegetables by Commodity (square metres) [5]

	2013	2014	2015	2016	2017
Tomatoes	5,626,971	5,540,993	5,513,837	5,990,278	6,325,725
Peppers	4,887,045	4,951,041	4,940,683	5,385,939	5,625,383
Cucumbers	3,462,183	3,544,039	3,739,159	4,005,746	4,358,064

Table E-2. Canada's Greenhouse Vegetable Exports by Commodity – Volume (metric tonnes) [5]

	2013	2014	2015	2016	2017
Tomatoes	126,869	133,955	125,327	140,083	152,617
Cucumbers and Gherkins	77,938	77,485	93,631	96,318	104,038
Peppers	73,858	76,685	82,317	83,114	83,582
Total	**278,666**	**288,125**	**301,275**	**319,515**	**340,237**

Table E-3 DLI Lighting Requirements per Crop (Preliminary Research)

Plant Type	DLI required for Minimum to Satisfactory Growth ($mol*m^{-2}*d^{-1}$)	Optimum Produce Quality DLI ($mol*m^{-2}*d^{-1}$)	Operating Temperature Range for Production Phase (Celsius)
Tomato	10-20	20-30 [29],[30]	Day: 20-22 [11], [30] Night: 18-20 [11], [30]
Pepper	10-20 [29],[30]	20-30 [29],[30]	Day: 21-24 [11] Night: 17-18 [11]
Cucumber	13-16 [11]	20-35 [11]	Day: 23-27 [11] Night: 17-21 [11]
Cannabis	Varies depending on method (see column to right) [30]	Standard Size Cannabis 65 [30] Sea of Green (high yield of small plant size) [30] Clone Phase: 1-3 Vegetation: 19 Flower: 48	Day/Night: 30 [30]