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Dynamic Distributed Energy Resources for Expansion of Ontario's Greenhouse Sector

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By

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Dynamic Distributed Energy Resources for Expansion of Ontario's Greenhouse Sector

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DECLARATION OF CO-AUTHORSHIP/PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

Chapter (II) of the thesis was co-authored with Gene Ingratta, Shalin Khosla, Xiuming Hao, under the supervision of professors Rupp Carriveau and Lindsay Miller. In all cases, the key ideas, primary contributions, experimental designs, data analysis, interpretation, and writing were performed by the author, and the contribution of co-authors was primarily through: Gene Ingratta contributed to the data analysis of the lit peppers; Shalin Khosla and Xiuming Hao contributed to the experimental design by providing design parameters used for the lighting recipes; Rupp Carriveau and Lindsay Miller provided feedback on refinement of ideas and editing of the manuscript and experimental design.

Chapters (III) and (IV) of the thesis were written under the supervision of Dr. Lindsay Miller and Dr. Rupp Carriveau. In all cases, the key ideas, primary contributions, experimental designs, data analysis, interpretation, and writing were performed by the author.

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Thesis Chapter	Publication title/full citation	Publication status*
Chapter [II]	*L. Naom, R. Carriveau, L. Miller, X. Hao, S. Khosla, and G. Ingratta, "Planning For the Massive Energy Impact Of Greenhouse Lighting in Ontario"*	*Submitted to Energy Nexus journal.*
Chapter [III]	*L. Naom, R. Carriveau, and L. Miller, "The Substantial Impact of the Greenhouse Sector on the Ontario Electricity Grid"*	*Prepared for submission in January 2023.*
Chapter [IV]	*L. Naom, R. Carriveau, and L. Miller, "Modelling A Five Greenhouse Network in Ontario With Distributed Energy Resource Designs"*	*Prepared for submission in January 2023.*

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ABSTRACT

The vegetable greenhouse sector is rapidly growing and adopting technology advances like supplemental lighting. Supplemental lighting has a dynamic impact on the demand and consumption of a greenhouse's electricity load. There is uncertainty on the rate of adaptation of technologies and the impact this could have on the power consumption of the sector. Without electricity availability, the sectors innovation and expansion can come to a halt. This research focused on investigating greenhouse electrical load models and lighting trends to forecast demand on electricity grids and discover potential for Distributed Energy Resource (DER) applications.

This thesis presents a series of studies developed and implemented with commercial greenhouse data and industry standards in Ontario. First, an electrical load model was developed using commercial greenhouse data to differentiate between unlit and lit greenhouse consumption. The use of ten commercial and literature-based combinations of lighting and fixtures resulted in certain combinations and fixtures providing significant electricity consumption savings but displayed a greater capital cost. This model also demonstrated a significant increase in electricity demand and consumption when applying lighting to an unlit pepper vegetable sector. An analysis was then conducted by forecasting the implications of 75% of the Ontario vegetable greenhouse sector adopting lighting. This model normalized the current sectors electrical grid and produced a grid multiplier for lighting scenarios varying in intensity, type, and harvesting area. The findings demonstrated that with careful lighting selection and limitations of lighting intensity, the electrical grid can implement guidelines to regulate and prevent extreme loads from the greenhouse sector. Lastly, an analysis was preformed to illustrate the demand and electrical consumption of five vegetable greenhouses, individually and as a five-grower network. DER designs including cogeneration and battery were developed for the greenhouses and five-grower network. The results show that by creating a network, there can be significant reduction in DER capacity and subsequently financial cost. Outcomes from this study confirm that creating greenhouse networks can allow for greenhouses to self-generate at a reasonable cost using DERs. Together these works combine to form a valuable analysis tool on the greenhouse sectors electrical load and provides potential solutions to moderate the power growth of the sector.

DEDICATION

In dedication to my loved ones for their continued support and understanding of the excuse "Sorry, I am working on my thesis".

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LIST OF ABBREVIATIONS/SYMBOLS

DER	Distributed Energy Resource
DLI	Daily Light Integral
HPS	High Pressure Sodium
IESO	Independent Electricity Sector Operator
LED	Light Emitting Diode
NG	Natural Gas
OGVG	Ontario Greenhouse Vegetable Growers
PAR	Photosynthetically Active Radiation
PPFD	Photosynthetic Photon Flux Density
SL	Supplemental Lighting
W	Wattage

CHAPTER I INTRODUCTION

1. BACKGROUND

Highlighted by the COVID-19 pandemic, food security and the need for self-sustaining communities is more apparent than ever [1]. By 2050, food demand is expected to grow by 56% [2]. To meet this demand, year-round growing seasons and technologies that promote increased yield are key. Due to this need, greenhouses have become a popular choice for growing produce as it allows for a controlled environment that protects the crop from external influences [3]. Recent innovations and advances have led to the Canadian greenhouse industry becoming successful in the global market and vital to the Canadian economy [4].

Canada is home to 837 commercial greenhouse operations with 71% of the total vegetable production occurring in Ontario [4]. The vegetable production is primarily cucumbers, peppers, and tomatoes. Although the industry has remained successful over the years, Ontario experiences seasonal changes resulting in shorter sunlight periods during the winter months. In greenhouse concentrated regions, the frost-free growing period is about half of the year [5]. This prevents high yields of produce occurring year-round. To allow for a high producing continuous growing season, innovative technologies are essential.

In seasonal locations, supplemental lighting allows greenhouses to provide their crop with light throughout the year [6]. Generally, it is stated that a 1% increase in lighting results in a 1%, yield increase [7]. The common types of greenhouse lighting include High Pressure Sodium (HPS) and Light Emitting Diode (LED). With supplemental lighting comes various fixtures and lighting recipes dependent on crop, greenhouse structure, and location [8–10]. In Figure I-1, the first Canadian lit pepper greenhouse, Allegro Acres, is pictured with LED lighting. Many studies highlight that both lighting options result in an increased product yield for cucumbers, tomatoes, and peppers when compared to a greenhouse without lighting [6,11–18]. However, with the addition of supplemental lighting comes the increase in power consumption and energy costs. Although HPS was traditionally the go to for greenhouses, these fixtures require a high electricity demand and are ultimately more expensive to operate. Electricity operators currently assume a 35-55% energy savings from LEDs [19]. Yet, LEDs are often shown at a different lighting operation level than HPS, creating a challenge for transparent electricity comparisons. Currently, there is a lack of genuine comparison of the lighting types considering utility electricity costs, various growing methodologies, and industry level lighting habits.

Figure I-1: Allegro Acres, Kingsville, ON

For this sector to innovate, there must be available and cost-effective electricity to implement these lighting structures. A significant challenge is the unknown installation rate and power requirements of supplemental lighting. The Independent Electricity System Operator (IESO) of Ontario reported in 2018 that only 4% of vegetable greenhouse area had lighting [20]. Based on a 2021 Ontario Greenhouse Vegetable Grower (OGVG) statistics this has grown an additional 15%, making up 19% of the greenhouse area. This emphasizes the rapid growth, showcasing an almost 5x increase in lighting technological adaptation in three years. To meet this exponential technology growth, reliable power supply must be available.

Although the Ontario electricity grid seems to have enough supply for the current demand, shortages are expected to occur starting in 2026 [21]. However, in the Ontario greenhouse hub cities Kingsville and Leamington, grid shortages are already an issue [22]. Currently, there are greenhouse customers unable to connect due to the shortage [22]. To mitigate this, there are projects to install over 1300 MW of transmission infrastructure to meet these growing demands [23]. Besides grid infrastructure upgrades which take years, electricity operators push for greenhouses to make energy efficient choices, such as switching from HPS to LEDs [19]. The lack of options at present creates implementation barriers when the greenhouse industry is looking to innovate and the electricity sector lacks the availability to implement the technology. For some greenhouses, turning to external resources has been a solution to avoid these issues with grid connection wait times and availability.

Since growers are focused on their crop, energy consumption has historically been overlooked and assumed to be available. With availability concerns emerging, distributed energy resources (DERs) are being proposed as a potential solution to grid supply shortages and growing electricity costs. DERs include a variety of technologies: solar, wind, cogeneration, batteries, and others [24]. Due to the nature of greenhouse operation, the

DER choice is not always simple. However, the Netherlands has proven cogeneration DERs to be an economical solution and widely adopted in this infamous greenhouse industry [25]. Cogeneration supplies a greenhouse with heat, electricity, and CO_2, all used to support crop growth [26]. Because of power supply shortages, cogeneration may be solution greenhouses look to implement in Ontario.

DERs can be off-grid solutions supplying a specific greenhouse location or a grid-connected solution allowing excess electricity generation to supply utility connected facilities. One of the main benefits of installing DERs off grid is that they allow greenhouses to innovate without the long term waits of utility approvals and installations [27]. For example, DT Enterprise Farms installed 2 MW of off grid cogeneration rather than wait for utility power supply and grid connection [28]. However, off grid solutions create a restriction in usability of installed assets as the energy can only be used within the greenhouse. This is especially important as a lit greenhouses load fluctuates dramatically. In the months with an abundance of sunlight, lighting is no longer needed. With the vast load difference between lighting months and non-lighting months, these assets can range from undersized to extremely oversized and may sit unused for months. Grid connected DERs have potential for use of this excess generation if electricity operators allow it. In Dutch greenhouses, the excess electricity is sold back to their utility as another income revenue [25]. However, in Ontario, currently there is a lack of understanding and modelling on the difference in electrical load between unlit and lit commercial greenhouses for this to be strategically used as well as limited grid connection availability.

Due to the limited access of industry data, few studies have been able to analyze and utilize electrical load data in commercial greenhouses. Currently, there is a knowledge gap on electricity operation trends between the greenhouse sector and the electricity industry. To date, no studies exist that look at greenhouses operating as a network for DER implementation. If this is leveraged, in greenhouse concentrated areas like Kingsville and Leamington, ON, DERs can enable innovation and provide the potential for businesses to collaborate. For the industries to work together to overcome future challenges, comprehensive research and understanding reflecting both perspective on the implementation of supplemental lighting and DER systems are necessary.

While some electricity operators believe switching to more efficient technologies like LEDs will address power shortages, the issue is much larger than anticipated. Both the electricity and greenhouse sector need to analyze usage and consider commodifying DERs as without this, the greenhouse industry will not be able to support global food demand. Since the greenhouse industry is vital to both global produce markets and the Canadian economy, the sectors growth and production should be supported.

2. OBJECTIVES

The objective of this thesis is to identify, quantify, and propose solutions to some of the challenges the Ontario greenhouse industry and electricity operator will have to face. This objective will be met through the following deliverables:

- Model Ontario based greenhouse electricity consumption for both unlit and lit greenhouses with a focus on load distribution, lighting types, and methodology impacts.
- Develop a detailed comparative analysis between an unlit and lit pepper greenhouse including lighting trends, electricity differences, and cost impacts with both a grower and electricity operator headset.
- Forecast the electricity consumption and demand impact of the entire Ontario greenhouse vegetable industry making a shift to supplemental lighting, crucial to grid planning.
- Model DER cogeneration systems for greenhouses; for both individual and networked operations, as an off-grid generation solution.

3. THESIS ORGANIZATION

Chapter II focuses on conducting an analysis of the supplemental lighting technologies and methodologies, with a focus on their impact to the pepper vegetable crop in Ontario. Currently, peppers occupy the largest greenhouse land space in Ontario but only one greenhouse operation uses supplemental lights. This study evaluates the difference between an unlit and lit pepper crop in Ontario and the influential electrical impact this decision could have. The study shows the electrical impact through a grower's lens, prioritizing fixtures, methodologies, and lighting targets based on ideal crop requirements. This lays the groundwork of the thesis by detailing the electrical load through the diverse methodologies of a grower and by projecting the potential load this sector can have. Further, this chapter highlights electricity usage for optimal crop health and yield, which is precedent to growers. This emphasizes the that reducing electricity is not the primary importance in the energy and agriculture nexus, the crop is.

The agriculture sector is a powerful and dynamic sector, however, the sector cannot operate a technology advanced front without a joint coordination with the electrical sector. Chapter III highlights the potential impacts of lighting most of the Ontario greenhouse vegetable sector to the electricity grid. This study focuses on lighting intensity, lighting technology splits, and analyzes the impacts of sector growth and lighting adaptation. This study shows the impact of supplemental lighting through an electricity operation lens, prioritizing greenhouse variables that correlate to grid power consumption. Average lighting intensities were used to establish the electrical consumption and demand from the sector today, while adaptation of specific lighting technology splits was modelled on both today's sector and a projected sector. This chapter highlights key parameters that can potentially be regulated for power consumption efficiency and models the intense loads the grid could face. Furthermore, it highlights that the sectors power consumption can be volatile and presents a case for exploring other avenues to meet these growing electricity demands.

Chapter IV ties in the needs of both the greenhouse operator and grid operator, a current barrier in the industry. With greenhouse operators wanting to innovate on their own timeline and grid expansions requiring long planning and execution periods, DERs are a solution to both industries. To begin five greenhouses of mixed crops and lighting habits were chosen in the greenhouse hub of Ontario. This study models electrical consumption and demand for the greenhouses as separate entities and as a five-grower network. Cogeneration and battery designs were created and analyzed to meet the loads of both the individual greenhouses and the five-grower network to determine if any value comes from a collaboration as such. This chapter evaluates potential DER cost and fuel savings with collaboration through a twenty-five-year evaluation. It highlights electricity operations, costs, and assets in a modern investigation that has not yet been explored. Overall, this chapter concludes a thorough analysis and understanding of electrical loads through a contemporary solution to issues faced by both the greenhouse and electricity industries in Ontario.

The three chapters in this thesis combine to provide a valuable modelling toolset for greenhouse and electricity system operators in a manner that has yet to be done. Using industry data, these models can be adapted and referenced to apply to greenhouse sectors globally. The insights gained through such study can significantly aid in future grid planning through the understanding of greenhouse electricity operation.

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CHAPTER II PLANNING FOR THE MASSIVE ENERGY IMPACT OF GREENHOUSE LIGHTING IN ONTARIO

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1. INTRODUCTION

The COVID-19 pandemic and the shutdown of international borders for trade and travel have impacted the Ontario greenhouse sector and increased the importance of local food production for communities [1,2]. Global food insecurity doubled from January to December 2020 and Canada depends heavily on the international fresh vegetable trade due to seasonal changes [3]. Therefore, further investment of innovative technologies for the agricultural sector is fundamental for food security and economic development [4].

Ontario's greenhouse sector is vital to the Canadian economy; it accounted for $3.2 billion in GDP in 2016 and is expanding four to five percent annually [5,6]. Currently, the Ontario greenhouse vegetable sector is composed of approximately 315 greenhouses planting cucumbers, peppers, and tomatoes [7]. These greenhouses account for 660 acres of cucumbers, 980 acres of tomatoes, and 990 acres of peppers, and the number of acres continue to grow [8]. With greenhouse vegetables being produced out of season, there are benefits of higher economic profit on the produce itself [9]. Given the COVID-19 pandemic and increases in operating expenses and labour shortages, innovation and expansion are key to ensuring that the greenhouse sector can respond to Canadians' nutritional needs [1]. Additionally, this innovation and expansion comes with an urgent need for analysis and solution to support this transition to year-round produce. Overall, consumer demand for year-round local greenhouse vegetables is increasing, therefore the Ontario greenhouse sector (and sectors like it) require(s) year-round solutions and the information to implement them. [10–14]

Seasonal changes impact the amount of natural sunlight that the crop receives, thereby challenging the ability to consistently grow to produce year-round without reliance on additional systems like supplemental lighting [15–18]. Supplemental lighting (SL) is more common in the Netherlands, Canada, and the northern United States due to the shorter day length during winter periods[19]. Around the globe this need only increases with increases in latitude. In an SL study on tomatoes, sweet peppers, and cucumbers, researchers found that Canada produced 15% more crop yield than the Netherlands, while also naturally receiving 15% more light [20,21]. This illustrates a common rule that generally, for every 1% increase in lighting, an increase of 1% in yield can be expected, although other crop measures including CO_2 influence this as well [22,23]. Currently, in Ontario's vegetable sector, supplemental lighting is commercially practiced for cucumber and tomato crops, whereas it is an uncommon practice for sweet peppers [24]. In 2019, Allegro Acres located in Kingsville, Ontario, was announced as the first commercial winter pepper grower in Canada, lighting four acres with LED lighting. Two years later, in April 2021, it was reported that 363 acres of cucumbers, 333 acres of tomatoes, and 4 acres of peppers use supplemental lighting in Ontario, making Allegro Acres still the only lit pepper grower in Ontario. While the pepper crop itself represents over a third of the Ontario greenhouse vegetable crops, only 1.5% of that crop uses supplemental lighting in comparison to 27% of all greenhouse vegetable crops. [8]. With the pepper industry being introduced to supplemental lighting in Ontario, there is an increase in interest from greenhouse operators to know if supplemental lighting is worth the investment. As this increase in interest turns into implementation, the greenhouse sector could face a massive change that must be planned for. This emphasizes the need to explore the interconnectivity of energy and food, as the growth in demand of food historically increases the need for energy [25]. Although this study is based in Ontario, exploring this new development of pepper supplemental lighting can easily be translated to other regions and will be a necessity to understand the disruption associated with it.

Supplemental lighting options, such as High-Pressure Sodium (HPS) and Light Emitting Diodes (LEDs), are common lighting fixtures used in greenhouses when natural sunlight is not available to maintain greenhouse crop production [26]. HPS lighting is known for its wide spectrum of light and radiative heat, which reduces greenhouse heating system loads, and it is currently seen as an industry standard [27–29]. LEDs, a new technology for lighting in greenhouses, have been shown to improve crop yield and quality in commercial crops [22]. Additionally, LEDs are smaller, faster switching, more durable and electrically efficient in comparison to HPS lights [27,30–33]. The increased energy efficiency of LED lights and the ability to select wavelength recipes according to what benefits the crop has made LEDs more appealing to the sector [29,34–37]. Given these options for supplemental lighting, greenhouses need to consider both HPS and LED fixtures for pepper crops and this paper will focus on different lighting combinations, electricity consumption and demand, and their electricity cost for commercial sweet pepper greenhouse vegetables.

While lighting pepper crops is relatively new in Ontario, the effectiveness can be evaluated by considering research practices and studies. In a Quebec study, in comparison to natural light, sweet peppers were shown to have an increase in crop yield up to 33% with an 18-h to 24-h photoperiod of supplemental lighting [23]. An HPS lighting study in Finland showed that with the lights at varying canopy heights the fruit yield increased by 23% [24]. Based on a toplight HPS and LED interlighting study, the pepper crop produced more yield and higher quality in comparison to HPS toplighting only [38] These LED interlighting studies have further shown a 16% and 25% increase in yield [38,39]. In a 2020 Michigan study on cucumber, tomato, and pepper transplants, it was found that in terms of desirable characteristics of the transplant, LED lighting was as effective as HPS lighting [40]. Based on these studies' lighting recipes, HPS lights, LEDs, and a combination of the two should be considered in a sweet pepper greenhouse, as all three offer benefits in yield. Supplemental lighting has been proven globally in research studies and in practice in commercial greenhouses. Although supplemental lighting is innovative and beneficial for productivity in the greenhouse sector, it is important to consider the challenges.

The introduction of supplemental lighting in a greenhouse result in increased costs. When adding supplemental lighting, capital costs associated with the fixtures and electricity costs to operate them become additional greenhouse expenses. Compared to general agricultural energy usage, greenhouses energy consumption is considered the largest consumer [41]. Energy in a greenhouse includes a heating system and an electrical system. The electrical load for unlit greenhouses is a combination of electricity to operate a gas boiler, irrigation systems, fans, pumps, and additional minor office equipment. Without supplemental lighting, energy costs (electricity and fossil fuels) are 20-30% of the total greenhouse production costs, whereas a recent study suggests that supplemental lighting electricity costs alone can amount to 30% of a greenhouse's expenses [42,43]. Although, the greenhouse's increase in electricity demand and consumption and thus electricity costs will differ depending on the choice of lighting fixtures, lighting strategies, and electricity prices [9,23]. This increase in electricity costs directly correlates with a dramatic increase for grid operators and utilities for electrical demand and consumption [44].

Considering industry-standard lighting fixtures, HPS lighting can range from 600W-1000W and LEDs 340-700W. In contrast, although HPS has a higher electricity operational cost, its capital cost is lower than LED [31,45,46]. Greenhouses are faced with the challenge of navigating the various lighting fixtures, recipes, and yields, leaving the electricity analysis of supplemental lighting overlooked. The lack of electricity analysis is critical and detrimental to areas where electricity supply is already limited as there is no impact analysis for greenhouse and electricity operators. Without this analysis, there is potential for supplemental lights to remain unused in a greenhouse as the electricity to power them will be unavailable without proper forethought.

Due to the lack of supplemental lighting in Ontario sweet pepper operations, there is less year-round pepper produce when compared with cucumbers and tomatoes. Considering the potential benefits of year-round availability, yield increase, and off-season sale prices, there is a sector need for an analysis of the capital and electricity costs of supplemental lighting in Ontario greenhouses. The purpose of this paper is to analyze the economic feasibility of the electricity costs for an unlit pepper crop and a pepper crop with supplemental lighting and the associated electricity changes. This analysis is pivotal for the sector as the electricity demand and consumption must be planned for by greenhouse and electricity operators to aid this vital need of sector growth. This study will outline the transition of an acre of unlit peppers to HPS lighting and LED lighting which can be used for grid planning when projecting the future electricity consumption of the sector. Variables that will be considered include greenhouse location and material, crop cycle, electrical consumption, and various lighting recipes and fixtures. Overall, this study includes an analysis outlining the unlit, HPS lit, and

LED lit pepper greenhouse crop and the associated electricity demand, consumption, and operational costs. Hence, the objective of this study is to analyze the implementation of supplemental lighting in a pepper greenhouse and its considerable impact on electricity consumption and cost to help project the electrical development of the sector. It should be noted that while peppers are one of three major greenhouse crops in this region, the total electrical lighting demand for cucumbers and tomatoes is of a similar magnitude.

2. METHOD

Sunlight conditions are analyzed near the greenhouse hub of Leamington, Ontario. Both an unlit double-polyethylene (poly) greenhouse and a glass greenhouse will be analyzed to understand the electrical demand and load of the unlit crop. Per acre, there can be marginal differences in the energy demand between poly and glass greenhouses. To develop a more diversely "representative" unlit pepper greenhouse we have averaged the electrical demand of the two sites. To model a lit pepper crop, a greenhouse base load and supplemental lighting load must be considered. The estimated electrical consumption of an unlit pepper crop also is here used as the base load of a lit pepper crop. To accurately model the diverse lighting options, different lighting fixtures and common lighting recipes are explored for the supplemental lighting load. The number of supplemental lighting fixtures will be found per acre and the associated electrical demand and annual consumption are calculated. Then, the base load is added to an averaged lighting design to represent a supplemental lit crop electrical load. The capital and electricity operation costs of a sweet pepper greenhouse with no supplemental lighting, with HPS lighting, and with LED lighting in Ontario will be estimated.

2.1. UNLIT SWEET PEPPER GREENHOUSE ELECTRICAL LOAD

The electrical load of an unlit greenhouse is influenced by the crop cycle, greenhouse covering material, and weather. Depending on these influencing factors, certain equipment will be used, leading to an increase or decrease in the electrical load. An analysis of an unlit 20-acre double-polyethylene and 24-acre glass greenhouse sweet pepper greenhouse will be completed to demonstrate the base electrical load. This will be completed by utilizing collaborating greenhouse facility hourly electricity data and normalized on a per acre basis.

2.2. CROP CYCLE

To understand where the fluctuation in the load occurs, the crop cycle for both greenhouses is presented in Table II-1. For instance, when the crop is planted, the irrigation system and boiler will be used to sustain the plant's healthy crop cycle and temperature. Typically, when there is no crop present, the empty greenhouse uses minimal electricity to prevent pipes from freezing. This creates changes in the electrical load, however, for this study, the crops will be averaged to provide a general understanding of a year-round load.

Table II-1: Greenhouse Crop Cycle

Greenhouse	*Planting Date*	*Tear out Date*	*Empty Time Period*
20 Acre Double-Polyethylene	December 15	November 15	Mid Nov – Mid Dec
24 Acre Glass	January 15	November 15	Mid Nov – Mid Jan

2.3. GREENHOUSE MATERIAL

To account for the difference in electrical requirements based on the greenhouse material, both a double-polyethylene and glass greenhouse will be examined. Depending on the greenhouse material, the transmissivity of a greenhouse varies which contributes to a variation in electricity usage to operate the boiler system [47]. The loads for these two greenhouses will be averaged as a per acre representation of an average unlit pepper greenhouse load.

2.4. LIT SWEET PEPPER GREENHOUSE ELECTRICAL LOAD

The electrical load of a lit greenhouse is influenced by the same factors as the unlit greenhouse and an additional supplemental lighting load.

2.5. SUPPLEMENTAL LIGHTING

Daily light integral (DLI) is the amount of photosynthetically active radiation (PAR) measured in mol per meter squared per day [48]. DLI represents the useful light that assists with plant growth. A target DLI for greenhouse peppers ranges from 16-18 mol/m^2-day [48]. To find the amount of natural sunlight that is useful to the greenhouse pepper crop, the natural sunlight, the transmissivity of greenhouse material, and the fraction of light need to be considered. On average, the transmission of natural sunlight onto the crop itself is 50% due to greenhouse material transmission as well as a blockage from the supplemental fixtures and pipes. Of the global solar radiation, only 50% of the fraction of light is useful to the crop as PAR [49].

To determine the amount of crop useful DLI in the greenhouse, the outdoor DLI near the Leamington, ON greenhouse hub area will be taken as the input natural sunlight. The natural sunlight will be based on a 20-year average of outdoor DLI in Harrow ON, located 33.5 km away from Leamington, ON. To find the crop useful DLI in the greenhouse, the natural sunlight will be multiplied by the 50% light transmissivity, and again by the 50% fraction of light. This is demonstrated by Equation 1 [49].

$$\boldsymbol{Crop\ Useful\ DLI\ in\ the\ Greenhouse = Natural\ Sunlight * 50\%\ Lighting\ Tranmission * 50\%\ Fraction\ of\ Light}\ \textbf{\textit{(Equation II-1)}}$$

The results from this calculation are shown in Figure II-1 as crop useful sunlight transmission.

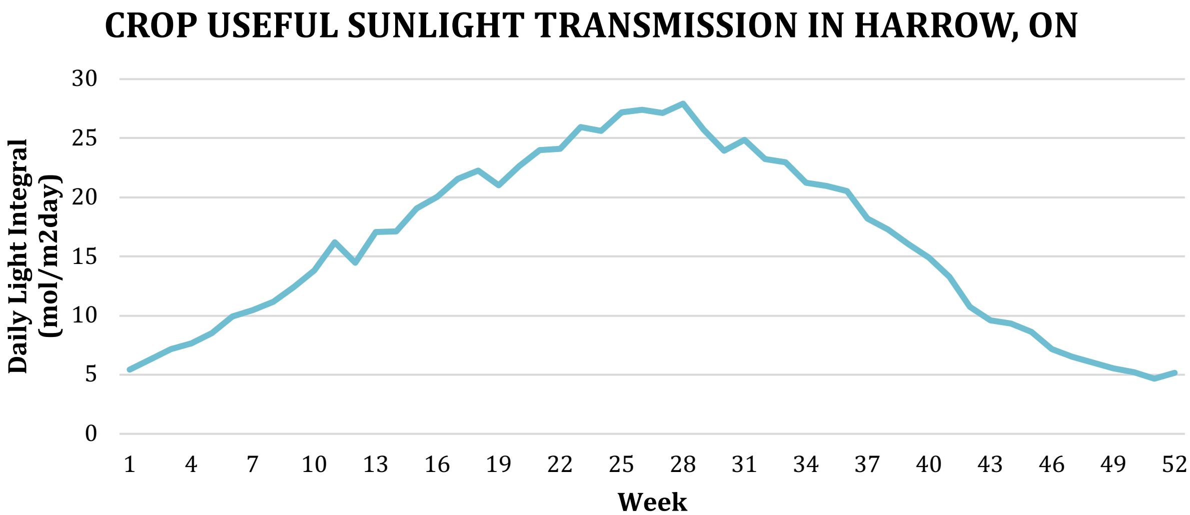

Figure II-1: 20 Year Daily Light Integral Natural Sunlight Transmission in Harrow, ON

To find the supplemental DLI needed, the crop useful DLI was subtracted by the targeted greenhouse DLI as shown in Equation 2. In this case, the targeted DLI was a range of 16-18 mol/m^2-day, resulting in approximately 21.3% of added light for the crop annually. The results of the supplemental DLI needs can be shown in Figure II-2.

$$\boldsymbol{Supplemental\ DLI\ (molm^{-2}day^{-1}) = Targetted\ Greenhouse\ DLI - Crop\ Useful\ DLI}\ \textbf{\textit{(Equation II-2)}}$$

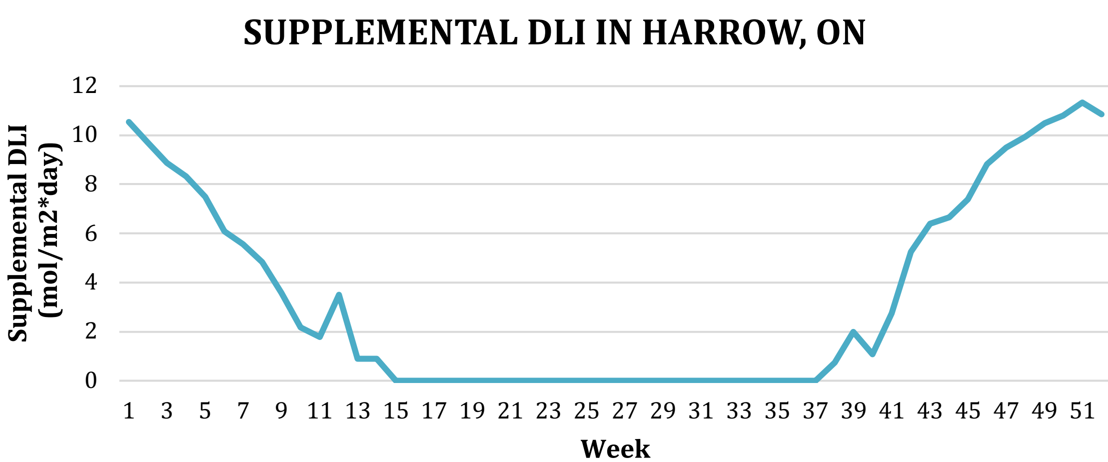

Figure II-2: Supplemental DLI in Harrow, ON

To meet these supplemental DLI targets both lighting cycle and fixture details must be considered.

2.6. LIGHTING CYCLES

Based on pepper studies, the recommended intensity is 150- 175 μmol/m^2/s for a 16-hour photoperiod [23,50]. However, further research states that under continuous lighting periods, the pepper crop can benefit, seeing an increase in yield of 33% for an 18-hour and 24-hour photoperiod in comparison with no supplemental lighting [50,51]. Generally, photoperiods of 16, 18, and 24-hour of supplemental lighting show an increase in yield as compared to solely natural lighting [24,50,52–54]. Using this information, sector expert knowledge, and practices used by greenhouse operators today, four lighting methods, as shown in Table II-2, will be considered to evaluate the impact of supplemental lighting on electricity consumption.

Table II-2: Lighting Methodology

Lighting Method	*Type*	*Intensity (μmol/m²/s)*	*Lighting Period (hrs)*
1	HPS	200	16
2	LED	200	16
3	LED	175	16
4	LED	(1) 160 then (2) 80	(1) 16 then (2) 8

2.7. LIGHTING FIXTURES

To perform this lighting method at a greenhouse, four lighting fixtures were chosen. This will be completed with one HPS lighting fixture and three different LED lighting fixtures. These fixtures are currently popular in sector practice and provide different customization abilities. For this study, the wattage and lighting output will be considered only. The four lighting fixture details are shown in Table II-3.

Table II-3: Lighting Fixture Details

Lighting Fixture	*Company*	*Model*	*Wattage (W)*	*Light Output (μmol/s)*	*Type*
A	Agrolux	ALF1000 HPS DE	1000	2100	HPS
B	Fluence	VR-3P-BW3	620	1680	LED
C	Signify	GPL TLC 2400 DRB_LB 277-400V 1.2D SB xP	700	2400	LED
D	Sollum Tech.	SF4	340	720	LED

2.8. LIGHTING COMBINATIONS

Using the information from Table II-2 and Table II-3 the following lighting method and fixture combinations will be explored: 1A, 2B, 2C, 2D, 3B, 3C, 3D, 4B, 4C, and 4D. To find the electricity consumption of these combinations the power of each fixture, the number of fixtures, and the annual hourly usage are needed.

First, the power of each fixture can be found in Table II-3 as Wattage (W). Next, the number of fixtures was calculated using Equation II-3 where fixture light output is found in Table II-3 and lighting recipe intensity is found in Table II-2.

$$\textit{Number of Fixtures per Acre} = \frac{4046.86\frac{m^2}{acre}}{\frac{\textit{Fixture Light Output}\ (\mu mols^{-1})}{\textit{Lighting Recipe Intensity}\ (\mu molm^{-2}s^{-1})}} \qquad \textit{(Equation II-3)}$$

The daily hours on can be calculated by Equation II-4 where supplemental DLI is taken from Figure 2 and intensity is taken from Table II-3.

$$\textit{Hours ON per Acre} = \frac{\textit{Supplemental DLI}(molm^{-2}day^{-1})}{\textit{Intensity}\ (umolm^{-2}s^{-1}) * 3600\frac{seconds}{hour} * \frac{1x10^{-6}mol}{umol}} \qquad \textit{(Equation II-4)}$$

This calculation was complete for a full year and done for the five lighting combinations. The results for the different lighting combinations are shown in Figure II-3.

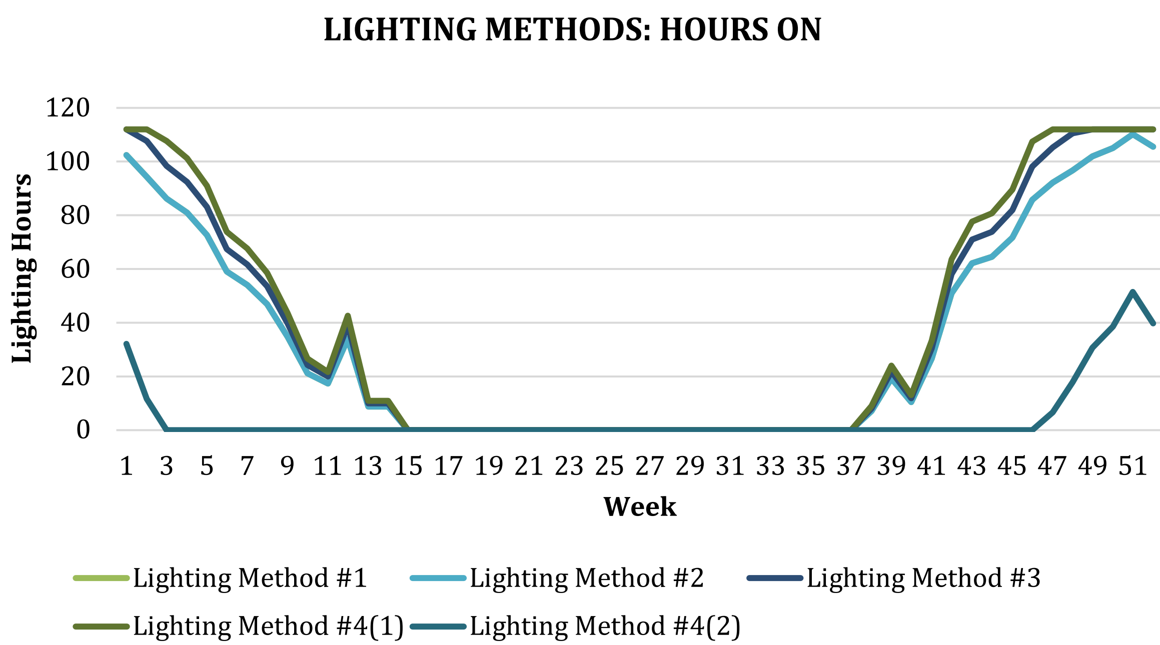

Figure II-3: Lighting Method Results Hours ON per Week

Electricity demand is the maximum one-hour period of electricity usage as defined by the electrical utility. Using the lighting fixture power (W) and the number of fixtures, the lighting electricity demand can be calculated by Equation II-5.

$$\textit{Lighting Electricity Demand}\ (kW/Acre) = \frac{\textit{Lighting Fixture Power}\ (W) * \textit{Number of Fixtures}}{1{,}000\frac{W}{kWh}}$$

(Equation II-5)

Using the lighting electricity demand and the annual hourly usage, the annual electricity lighting consumption can be calculated by Equation II-6.

$$\textbf{Annual Electricity Consumption (MWh)} = \textbf{Lighting Electricity Demand (kW)} * \textbf{Annual Hourly Usage} * \mathbf{1,000}\,\frac{kW}{MW} \quad \textit{(Equation II-6)}$$

Overall, the number of fixtures, annual hourly usage, demand (kW), and annual electricity consumption (MWh) per acre for these lighting combinations are summarized in Table II-4.

Table II-4: Summary of Lighting Combination Results

PER ACRE	1A	2B	2C	2D	3B	3C	3D	4B		4C		4D	
NUMBER OF FIXTURES	385	482	337	1,124	422	295	984	385	193	270	135	899	450
ANNUAL HOURLY USAGE (HOURS)	1,732	1,732	1,732	1,732	1,939	1,939	1,939	2,051	229	2,051	229	2,051	229
LIGHTING DEMAND (KW)	385	299	236	382	261	207	334	239	119	189	94	306	153
ANNUAL LIGHTING CONSUMPTION (MWH)	667	518	409	662	507	400	649	517		409		662	

2.9. UNLIT AND LIT CROP ELECTRICAL LOAD MODELLING

The unlit sweet pepper greenhouse will be modelled by averaging the glass and double poly greenhouses electrical load by acre. Next, the supplemental lighting combinations demand and electrical consumption will be shown. To model a lit sweet pepper greenhouse, the averaged per acre electrical load for an unlit crop will be used as the base load. This base load will then be added to the lighting electrical consumption to find the total electrical load of a lit sweet pepper greenhouse. The lighting recipe 1A will be used to show an estimated electrical consumption of an HPS lit acre. The LED recipes 2, 3, and 4 and fixtures B and C were averaged. From there, an average power value of 660W, 397 fixtures per acre, and 1945 annual lighting hours were used to represent a LED lit pepper greenhouse which results in consumption of 509,629 kWh per acre a year.

2.10. COST ANALYSIS

To fairly determine the cost differences between HPS and LEDs, both capital and operational costs must be considered. Capital costs per acre can be calculated by using the fixtures per acre and the cost per fixture. Based on a local provider to the Leamington/Kingsville area, a capital cost of $240 CAD per HPS fixture and $1,000 CAD per LED fixture will be modeled. In this case, installation costs were not considered. Operational costs per acre requires the annual electricity consumption and the electricity cost. Using the fixture power values, the fixtures per acre, and the annual lighting hours for both HPS and LED lighting recipes, the annual electricity consumption can be calculated. For electricity cost, in Ontario, customers are charged different rates based on their average monthly peak demand [55]. Customers are charged as Class A customers if their demand is greater than 500 kW and as Class B if their demand is less than 500 kW [55]. To accurately represent the current greenhouse sector, both rates will be included. Modelling this based on 2019 electricity costs in Ontario, an annual average electricity rate of $0.03/kWh will be used for a Class A customer and $0.13/kWh for a Class B customer.

2.11. YIELD ANALYSIS AND SIMPLE PAYBACK PERIOD

Based on statistics in Ontario taken from the Ministry of Agriculture, Food and Rural Affairs, in 2021 the average production of greenhouse peppers in lbs per acre is 227,782 [56]. Early field trials of the lighting types engaged in this study revealed an anecdotal correlation that for every 1% of added lighting roughly equates to 1% of yield. This approximation of the increase in yield is calculated per acre based on the percent increase of annual lighting. In this study, the increase in lighting is approximated to be 21%. Based on statistics in Ontario taken from the Ministry of Agriculture, Food and Rural Affairs, the average price of greenhouse peppers in 2021 was $1.32/lb [56]. Applying the percent increase in lighting to the average lbs per acre, the average lbs per acre for a lit crop can be calculated. To find the annual sale dollars per acre of peppers, the average price of greenhouse peppers and the average yield will be used.

The simple payback period will then be calculated using the capital costs of the fixtures, additional crop yield profit, and annual electricity costs as shown in Equation II-7.

$$\boldsymbol{Payback\ Period\ (yr)} = \frac{\boldsymbol{Capital\ Cost}\ (\$)}{\left(\boldsymbol{Crop\ Yield\ Profit}\left(\frac{\$}{yr}\right) - \boldsymbol{Electricity\ Costs}\left(\frac{\$}{yr}\right)\right)} \quad \textbf{\textit{(Equation II-7)}}$$

2.12. ONTARIO PEPPER INDUSTRY GRID PROJECTION

The addition of supplemental lighting is not only impacting the greenhouses installing them but also the electricity grids that must supply the electrical load. To project this potential surge in demand, the electricity consumption and demand will be modelled for both HPS and LED at 0%, 50%, and 100% of the acres using each technology. Based on statistics from the Ontario Greenhouse Vegetable Growers (OGVG), it was reported in 2020 that there are 990 acres of greenhouse peppers. After conducting the annual electricity consumption and maximum electricity demand analysis, this will be applied to the total acreage of peppers. This analysis is crucial for future grid planning as the need for agricultural product and thus consuming innovation like supplemental lighting surges.

3. RESULTS AND DISCUSSION

3.1. UNLIT SWEET PEPPER ELECTRICITY LOAD

First, the monthly electricity demand (kW) per acre was assessed for both the glass and double poly greenhouse. The results for each month of the unlit pepper crops are shown in Figure II-4. Due to the nature of the crop cycle and the greenhouse material, the demand is higher in a double poly greenhouse in January to July and December. If the demands for these greenhouses are examined as an annual total, the electrical demand in a double poly greenhouse is 8% more than a glass greenhouse.

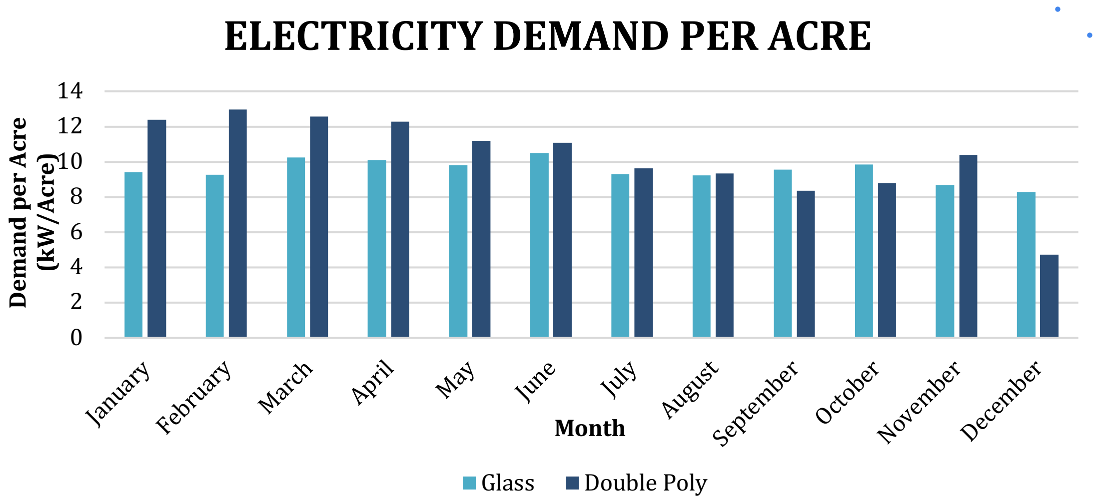

Figure II-4: Monthly Electricity Demand per Acre of an Unlit Pepper Greenhouse

Next, the total consumption (kWh) per acre was analyzed for both greenhouses as shown in Figure II-5. This is the monthly total electricity consumption used per acre of the unlit pepper crop greenhouse. When comparing the annual electricity per acre which includes one full crop cycle of an unlit pepper greenhouse, the consumption is 11% more for a double poly greenhouse.

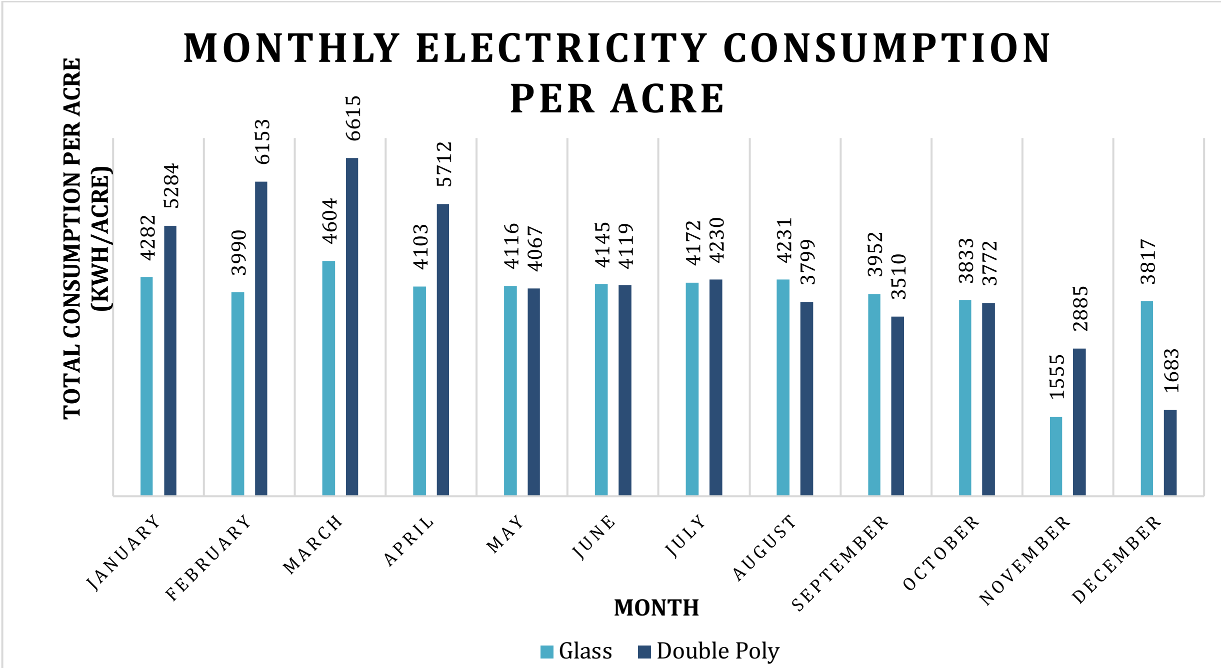

Figure II-5: Monthly Electricity Consumption per Acre of an Unlit Pepper Greenhouse

With both unlit pepper greenhouses modeled per acre, these values can be averaged and taken as the base load of a lit greenhouse. The average monthly electricity demand and monthly electricity consumption can be found in Figure II-6 and Figure II-7 respectively.

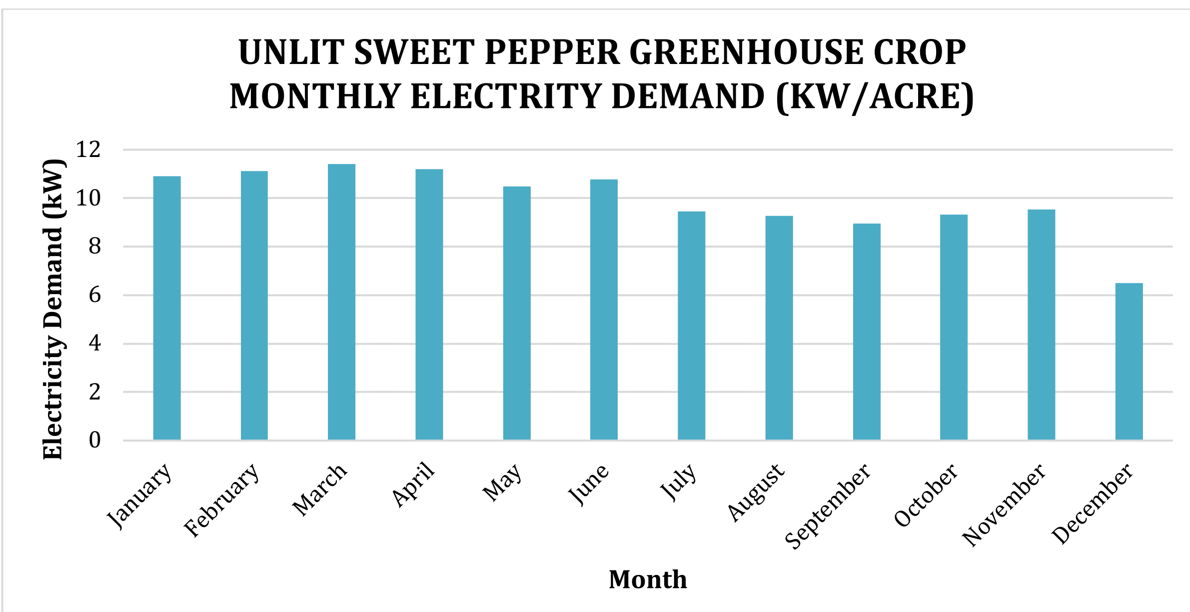

Figure II-6: Unlit Sweet Pepper Greenhouse Crop Monthly Electricity Demand (kW/Acre)

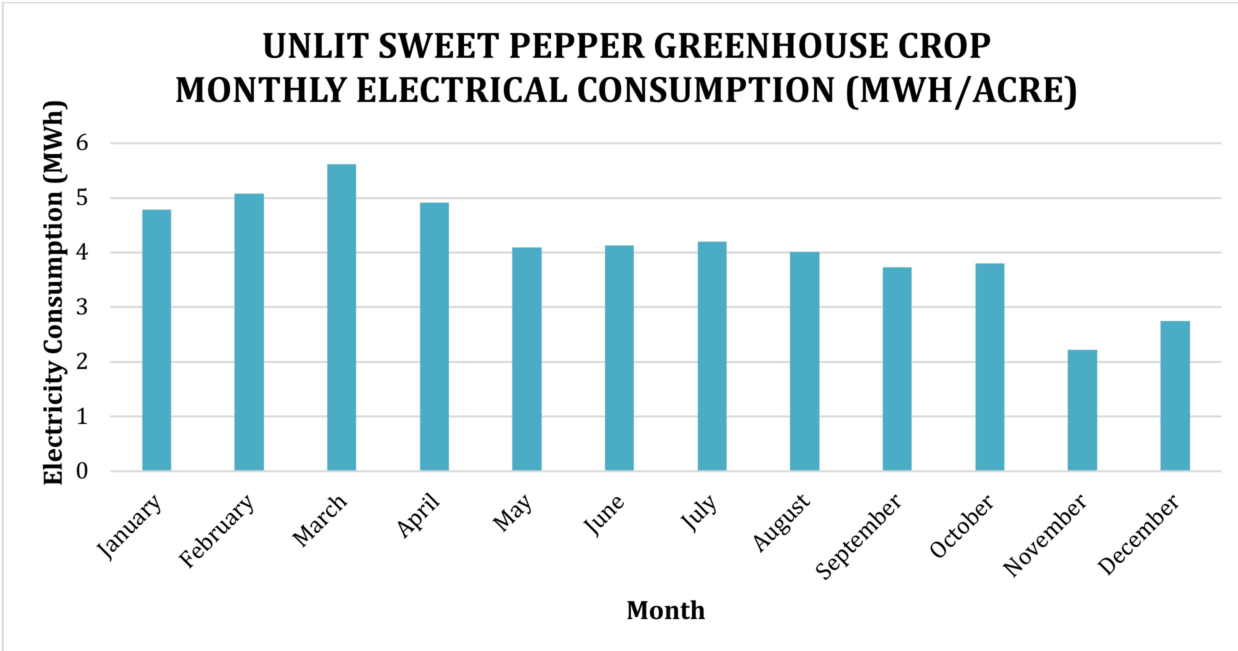

Figure II-7: Unlit Sweet Pepper Greenhouse Crop Monthly Electricity Consumption (MWh/Acre)

3.2. LIT SWEET PEPPER ELECTRICITY LOAD

Similarly, the results of the supplemental lighting recipes are shown as electrical demand in Figure II-8 and monthly electrical consumption in Figure II-9. Comparing the lighting methods, HPS generally use more than the LED fixtures, however, the consumption is close when using specialty LEDs like fixture D. In terms of lighting recipes, recipe 4 uses the least amount of electricity followed by recipe 3 and 2 respectively.

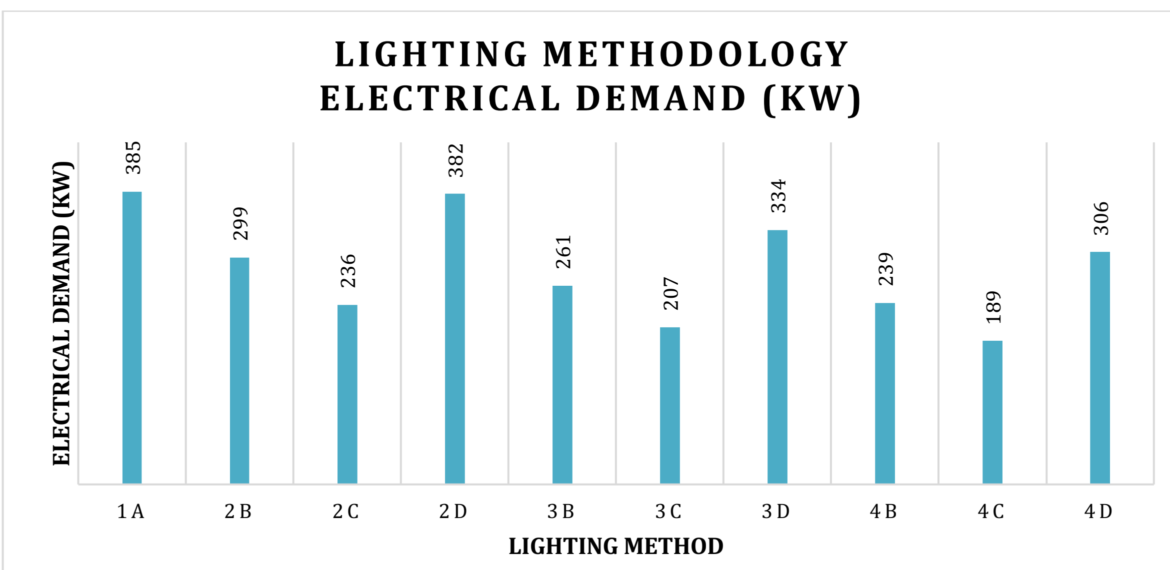

Figure II-8: Lighting Methods Electrical Demand (kW)

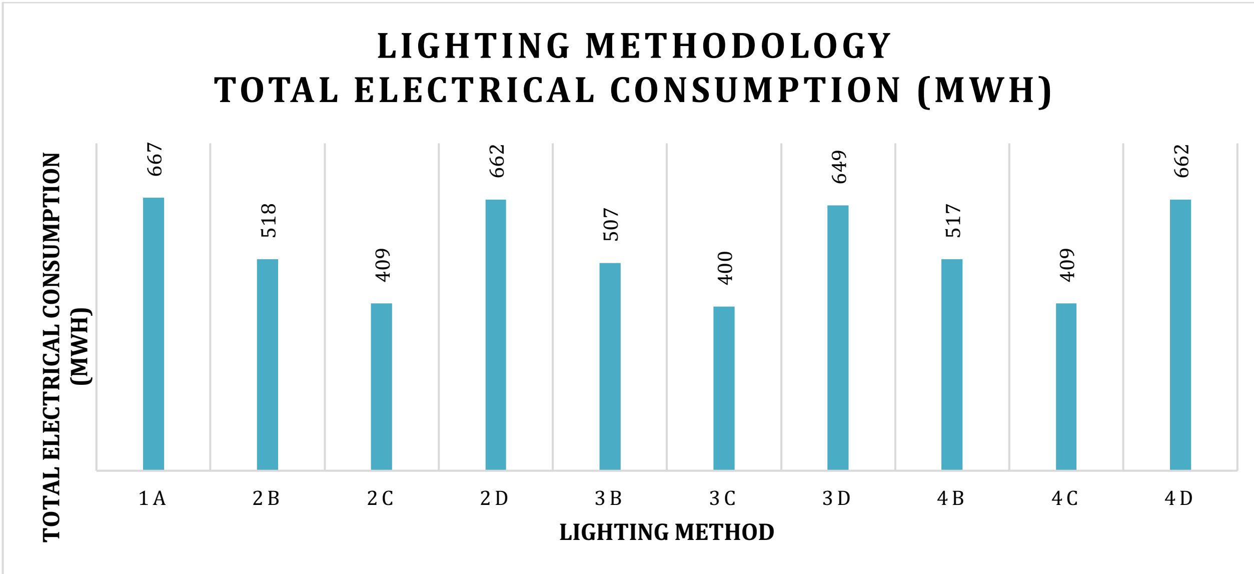

Figure II-9: Lighting Methods Total Electrical Consumption (MWh)

3.3. UNLIT, HPS LIT, AND LED LIT SWEET PEPPER ELECTRICITY LOAD

First, the unlit pepper greenhouse load is used to represent no supplemental lighting and is also the base load for the lit models. This base load is then added to the HPS lighting method to represent HPS lighting. Lastly, the base load is added to the LED average to represent LED lighting. The comparison between an unlit acre, a HPS lit acre, and a LED lit acre's electricity demand and monthly consumption can be found in Figure II-10 and Figure II-11 respectively.

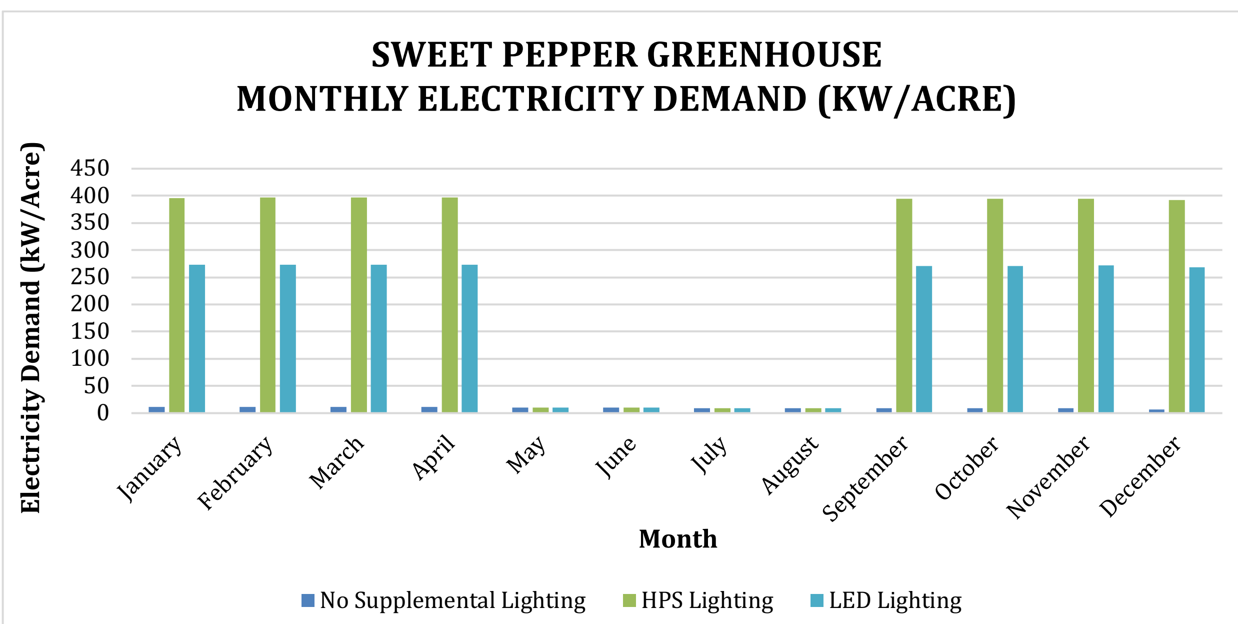

Figure II-10: Sweet Pepper Greenhouse Monthly Demand (kW/Acre)

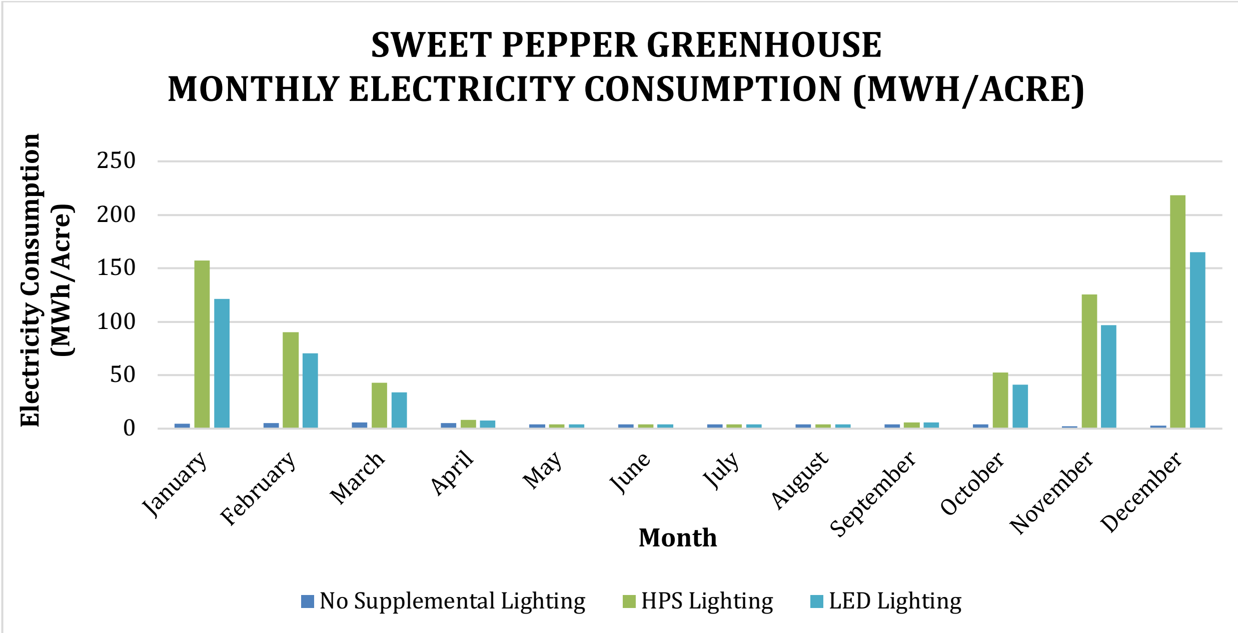

Figure II-11: Sweet Pepper Greenhouse Monthly Electricity Consumption (MWh/Acre)

Analyzing these values, on average, an HPS and LED lit crop have 27x and 19x more monthly demand than the unlit crop. It can be stated that on average an HPS lit greenhouse uses 15 times more electricity annually compared to an unlit pepper greenhouse. Similarly, an LED lit greenhouse uses 11 times more electricity annually compared to an unlit pepper greenhouse. Comparing an LED lit greenhouse to an HPS greenhouse, approximately 25% of annual electricity can be saved by using LEDs.

3.4. COST ANALYSIS

Based on the HPS and LED lighting assumptions, the cost per fixture, and the Ontario Class A and Class B electricity charges, an estimate of capital and operational costs for an HPS and LED customer are shown in Table II-5.

Table II-5: CAPEX and Operational Costs

SPECIFICATION	LIGHTING TYPE		
	Unlit	HPS	LED
FIXTURES PER ACRE	-	385	397
COST PER FIXTURE	-	$240	$1,000
CAPEX	-	$92,400	$397,000
ANNUAL ELECTRICITY CONSUMPTION (KWH) PER ACRE	49,314	716,134	559,006
CLASS A RATE ($/KWH)	$0.03		
CLASS B RATE ($/KWH)	$0.13		
CLASS A CUSTOMER COST PER ACRE	$1,479	$21,484	$16,770
CLASS B CUSTOMER COST PER ACRE	$6,411	$93,097	$72,671
CLASS A LED ELECTRICITY SAVINGS	-	$4,714	
CLASS B LED ELECTRICITY SAVINGS	-	$20,427	

From these results, a few observations can be made. Adding HPS and LED lighting can increase annual electricity costs by 14.5x and 11.3x more in comparison to unlit. When comparing HPS and LED capital costs per acre, LEDs cost 4.3x more. Analyzing the operational values, a HPS customer pays 31% more than if they were operating LED lighting.

3.5. YIELD ANALYSIS AND SIMPLE PAYBACK PERIOD

Due to a 21% increased exposure to lighting, the crop yield increases by the same factor resulting in an average production of 273,338 lbs/acre. While the unlit acre would have an average pepper sale of $300,672, the lit acre would have $360,806, approximately a $60,000 increase.

Taking into consideration the capital cost and profits from the addition yield due to the lighting, a baseline simple payback period can be determined. For a Class A electricity customer, the payback period for HPS and LED is approximately 2.9 and 9.5 years respectively. For a Class B electricity customer, since the cost of operating lights on this electrical cost structure exceeds the profit from the additional yield, it is not feasible to light an acre or more at this rate structure. However, if additional profits are explored such as the impacts of heat energy from lighting, this may have a different outcome.

3.6. ONTARIO PEPPER INDUSTRY GRID PROJECTION

Without adequate grid capacity, the Ontario greenhouse industry's widespread usage of supplemental lighting can be severely delayed. The annual grid consumption and maximum demand for all acres of Ontario greenhouse peppers can be found in Table II-6. Assuming 100% of these acres turn to HPS and LED lighting, this increases the grid consumption by 15x and 11x. These values are especially inflated when looking at the impact of demand if all acres turned to lighting, increasing by 35x and 24x for HPS and LED.

Table II-6: Projections for the Ontario Pepper Industry

	0%		**50%**		**100%**	
	HPS	**LED**	**HPS**	**LED**	**HPS**	**LED**
Grid Consumption (MWh/year)	48,820	48,820	378,894	301,143	708,968	553,465
Grid Consumption Multiplier	1	1	8	6	15	11
Demand (MW)	11	11	202	141	392	271
Demand Multiplier	1	1	18	12	35	24

4. CONCLUSIONS

Supplemental lighting enables commercial greenhouses produce during the low light winter months and greater yields, this contributes to evolving demand for local produce, a growing population, and food security. The addition of this supplemental lighting also creates an inflation of electricity demand and consumption. The analysis of an unlit Southern Ontario pepper greenhouse provides a benchmark electricity demand profile that may be referenced and compared to other regions. By exploring various lighting fixtures and recipes, which can be applied globally, pepper greenhouses and electricity operators will now have a better understanding of the corresponding electrical loads and demands to avoid the potential disruptive impact and appropriately grid plan. As interest in year-round growing continues to expand, supplemental lighting loads will become much more common, modelling and understanding the influence of these massive loads is critical to avoid electricity disruption. Based on the results of this study, the following conclusions can be made about the electricity consumption, demand, capital costs, operational costs, and payback periods of unlit, HPS lit, and LED lit greenhouse produced sweet peppers in Ontario.

Compared to the unlit crop:

1. The addition of HPS lighting on average would increase the demand load by 27x.
2. The addition of HPS lighting on average would increase the annual electrical load by 15x.
3. The addition of LED lighting on average would increase the demand load by 17x.
4. The addition of LED lighting on average would increase the annual electrical load by 11x.
5. When comparing LED lighting to HPS lighting, approximately 25% of annual electricity and 30% of annual average demand can be saved.

Comparing unlit, HPS, and LED capital and operational costs as well as payback period in Ontario:

1. LEDs capital cost is 4.3x more HPS.

2. HPS and LEDs increase annual operational costs by 14.5x and 11.3x compared to unlit peppers.
3. Operating LED lighting instead of HPS has a 31% electricity savings.
4. Class A customers have a HPS and LED lighting payback of approximately 3 years and 10 years respectively.
5. For Class B customers, installation of supplemental lighting without exploring additional funding or profits is unfeasible.

Projecting supplemental lighting to the entirety of the Ontario greenhouse pepper industry illustrates the sectors growth impact on the electricity grid. All acres adapting supplemental lighting would multiply the current assumption of load by the following:

1. HPS lighting increases electricity consumption and demand by 15x and 35x.
2. LED lighting increases electricity consumption and demand by 11x and 24x.
3. LED lighting can reduce the demand by 121 MW in comparison to HPS lighting.

Although the main electricity consumption is dependent on sunlight trends in southwestern Ontario, the difference and analysis between lighting recipes and the electricity demand can be applied internationally. The electricity and fixture costs, total electricity consumption, and overall comparison of annual electrical load is southwestern Ontario dependent. This investigation of supplemental lighting can be used as a planning tool to help characterize the future electricity demand of this and similar greenhouse sectors.

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CHAPTER III THE SUBSTANTIAL IMPACT OF THE GREENHOUSE SECTOR ON THE ONTARIO ELECTRICITY GRID

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1. INTRODUCTION

The technologically advanced greenhouse sector in Canada is led by the province of Ontario, representing 71% of the country's vegetable production [1]. There are concerns surrounding the ability for the Ontario's electricity sector to meet the growing agriculture demand. The electricity consumption and demand of the greenhouse industry depend on two major factors: sector expansion and technology adaptation. The volatility of the sector is influenced by variations in food demand, production costs, market pricing, and labour [2]. Due to these changes, it is often difficult to accurately forecast the industry growth corresponding electricity needs. For the electricity grid to accurately plan for the sector growth, it is crucial to understand the implications of the sectors expansion and technology adaptation.

As the harvested area increases, the electricity consumption naturally follows. The Ontario vegetable greenhouse industry expanding its harvesting area by 18% from 2016 to 2020, averaging at 4.5% per year [1]. Based on a 2021 Independent Electricity Systems Operator (IESO) study, the agriculture sector is expected to continue to expand at a rate of approximately 4% per year [3]. Although this gives a relatively consistent idea of sector area expansion, predicting the impact on the electrical grid is challenging when the rate of technology adaptation of greenhouses is unknown.

Technology adoption in the greenhouse space provides many benefits. Automation in the space includes climate control systems, drip irrigation systems, robotic systems, and supplemental lighting systems. Climate control systems allow for crops to grow in an optimal environment. These sensor driven systems monitor temperature levels, CO_2, humidity, climate screens, lighting levels, and more [4]. Drip irrigation systems allow for water to reach the plant at the root leading to better quality produce, reduced water waste, and labour savings [5]. Robotic systems such as spray systems and packaging lines allow for reduced labour cost, higher efficiency, and consistency [6]. Supplemental lighting systems such as High-Pressure Sodium (HPS) and Light Emitting Diode (LED) lights help increase crop yield and allow for year-round production [7]. Overall, technology enhances production and contributes to a resilient greenhouse system.

Although technology provides many benefits, the adoption of it often comes with a change in electricity consumption. Relative to the supplemental lighting systems, climate control systems, drip irrigation systems, and robotic systems consume minimal electricity, especially when the energy, labour, and water savings from these systems are considered [8,9]. On the other hand, supplemental lighting systems lead to a substantial increase in electricity consumption [10]. HPS and LEDs are the two common types of lighting systems implemented in greenhouses [11]. LED systems provide substantial electricity savings, however they increase heat energy requirement as they emit less heat than the traditional HPS [12,13]. The electricity grid in this case sees some relief but it should be noted that the energy demand shifts to other resources such as natural gas and fossil fuels as most greenhouses use gas powered boilers to heat their greenhouses [14]. Overall, this leaves the question of why is supplemental lighting needed and how extensively can it impact Ontario's demand?

With global food insecurity rising there has been a need for greenhouses to increase their crop yield [15–17]. In Ontario, the seasonal changes do not allow for considerable year-round crop growth without supplemental lighting, especially in the months with minimal sunlight [18–21]. This has created an expectation that vegetable greenhouses will be shifting to supplemental lighting and ultimately has led to the prediction of increased electricity usage from the industry [22]. Prior to 2018, Ontario Greenhouse Vegetable Growers (OGVG) did not track supplemental lighting due to minimal number of installations. Based on OGVG data, the adoption of supplemental lighting in 2018 and 2019 in the sector was 9%. In 2021, OGVG reported that 19% of the Ontario greenhouse vegetable sector utilize lighting. For a greenhouse, lighting can account for up to 30% of a greenhouse's operational costs [23]. Despite this, the number of greenhouses installing supplemental lights in Ontario increases each year due to consumer demand and overall advantages. While the addition of supplemental lighting will help with crop yield and clearly provides substantial value to the sector, this creates additional pressure onto local distribution systems and provincial electrical generation. When considering supplemental lighting, the question of electricity availability is now a more common issue.

For adequate electricity availability, sector expansion needs to be projected accurately for grid planning purposes. In a 2019 IESO Greenhouse Energy Profile Study, it was predicted that the entire Ontario greenhouse industry would have an electricity consumption of 3.9 TWh in 2024 [24]. In that same report, the vegetable sector was predicted to increase to 1.81 TWh in 2024, representing almost half of greenhouse electricity consumption. In preparation for the electricity increases, $1 billion dollars have been invested in Ontario transmission projects [25]. However, these upgrades will take up to 8 years to complete and may not even be able to meet these new demands due to rapid technology adaptation rates. This emphasizes the need for current lighting projections for Ontario and the corresponding electricity demand and consumption.

Although distribution expansions have been made to match the potential agricultural electricity increases, the impacts to the Ontario electricity grid with sector expansions and lighting adaptations are largely underexplored. To achieve a world class greenhouse industry, the province requires the availability of electricity to support it. The purpose of this study is to reflect the electricity implications of HPS and LED lights to the Ontario vegetable greenhouse sector. This will be done by quantifying the electricity the current sector uses and applying both sector expansion and lighting adaptation trends until only 25% of the sector remains unlit with a combination of scenarios. Ultimately, these results can be used for sector expansion and lighting adaptation estimations and grid planning.

2. METHOD

To project the potential consumption of the Ontario vegetable greenhouse industry, an analysis of the current sector, lighting trends, and current electrical load has been conducted. First, the current state of the Ontario greenhouse vegetable was analyzed including total acres, unlit acres, and lit acres split by lighting type for cucumbers, tomatoes, and peppers. Next, the required amount of supplemental lighting was found based on natural sunlight trends in the greenhouse hubs Kingsville, ON and Leamington, ON. From here, HPS and LED lighting strategies were analyzed from research data and averaged for projection purposes. Total electrical requirements for both unlit and lit greenhouses were then determined. Lastly, the current greenhouse sector consumption was estimated as a baseline for the projections. The grid electrical demands and consumption of cucumber, tomato, and pepper greenhouses turning on their light in Ontario will be projected in various scenarios of lighting technology breakdown and strength.

2.1. ONTARIO GREENHOUSE VEGETABLE SECTOR OVERVIEW

Based on the 2021 Ontario Greenhouse Vegetable Growers (OGVG) data, the number of total acres, unlit acres, and lit acres can be found in Table III-1. The lit acres are also split up by number of HPS and LED acres.

Table III-1: Ontario Greenhouse Breakdown

	ACRES	UNLIT ACRES	LIT ACRES	HPS ACRES	LED ACRES
CUCUMBERS	975	614	361	266	95
PEPPERS	1365	1353	12	0	12
TOMATOES	1211	907	304	215	89
TOTAL	3551	2874	677	481	196

The unlit versus lit data is modelled in Figure III-1. This demonstrates that many vegetable greenhouses remain largely unlit and have the potential to install supplemental lighting.

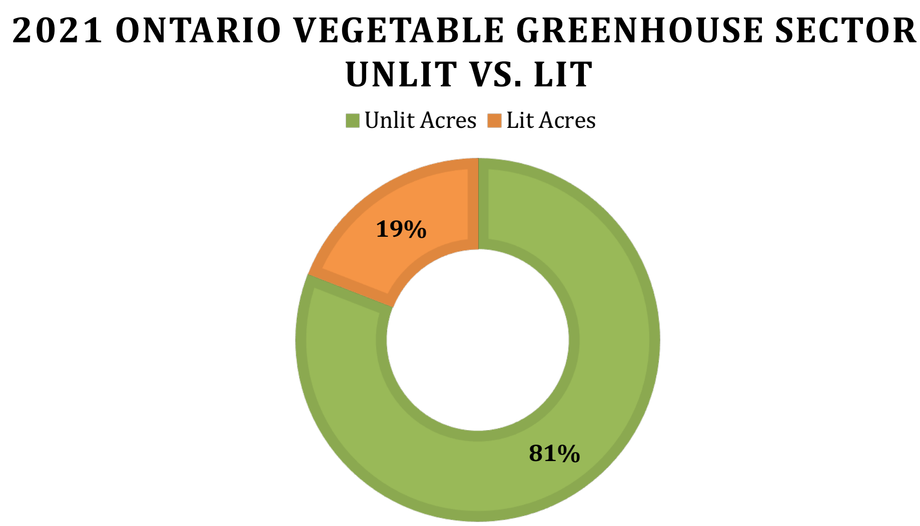

Figure III-1: 2021 Ontario Vegetable Greenhouses Unlit and Lit Acres

Breaking down these statistics even further, the acres are split by type and lighting status in Figure III-2. This figure demonstrates that lighting peppers in the industry is rare, over half the cucumber acres are lit, and one-third of tomato acres are lit as well.

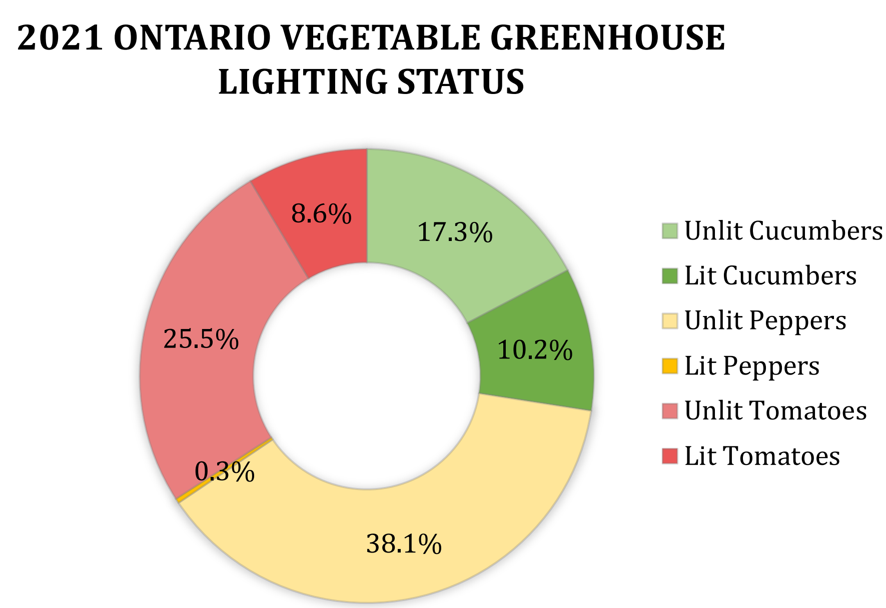

Figure III-2: 2021 Ontario Vegetable Greenhouse Lighting Status by Crop Type

2.2. LIGHTING STRATEGIES

To model the common lighting strategies for greenhouses, research was done on common lighting hours and fixtures for cucumbers, tomatoes, and peppers. The amount of natural lighting the crop receives in the greenhouse and the amount that is ideal for the crop were quantified. Once quantified, the amount of supplemental lighting that is needed was found. From here, an average lighting intensity was chosen as well as an average HPS and LED fixture. Once chosen, the number of lighting hours and fixtures needed to satisfy this can be approximated which then contributes to electrical projections.

2.3. DAILY LIGHT INTEGRAL

The daily light integral (DLI) is the total amount of light that a plant receives in one day, often measured in $mol \cdot m^{-2} \cdot d^{-1}$ or moles per day [26]. The amount of supplemental lighting DLI needed is found by the difference of natural DLI and the target crop DLI. The target DLI often varies by crop and is determined by researchers and crop specialists. The target DLI is between 20 to 35 $mol \cdot m^{-2} \cdot d^{-1}$ for cucumbers, 20 to 50 $mol \cdot m^{-2} \cdot d^{-1}$ for tomatoes, and 25 to 50 $mol \cdot m^{-2} \cdot d^{-1}$ for peppers are between [27]. The natural DLI comes from the sunlight. For consistency, a point between the greenhouse hubs in Ontario: Kingsville and Leamington will be chosen and used for all acres across Ontario. Using SunTrackers DLI calculator, at longitude and latitude 42.05, -82.67, the natural DLI in the area as shown in Figure #3 [28]. Based on commercial greenhouse transmissivity, about 70% of natural light makes its way to the crop, this is shown as natural greenhouse DLI in Figure III-3 [29].

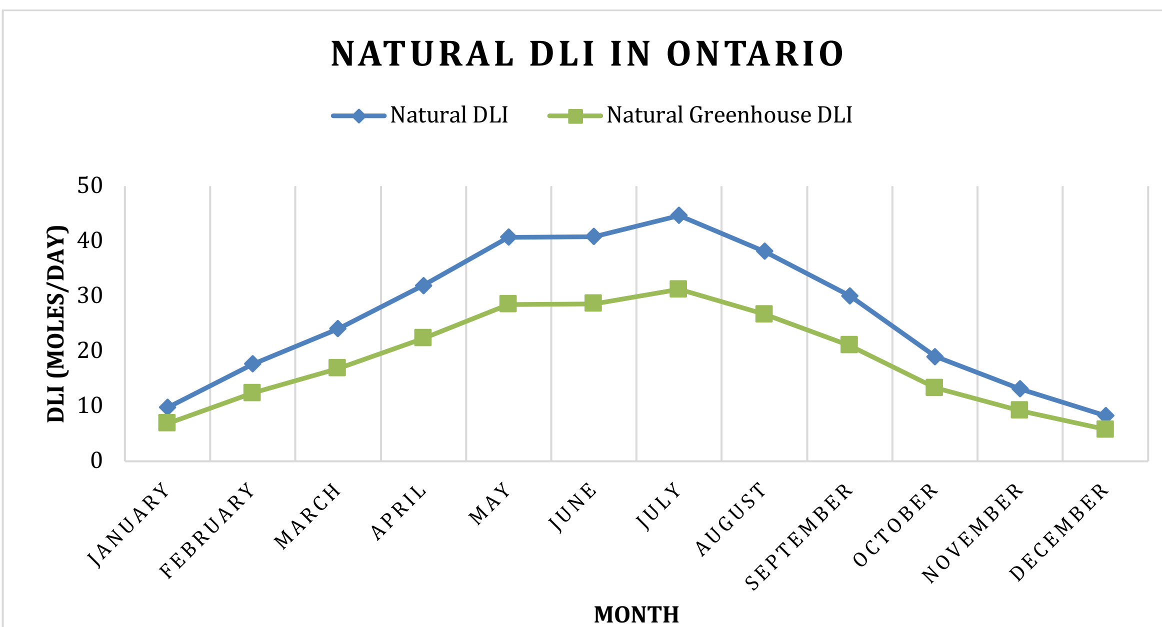

Figure III-3: Natural DLI in Ontario

2.4. NUMBER OF FIXTURES

Lighting intensity, also known as the photosynthetic photon flux density (PPFD) is the light measured over an area often measured in µmol m^{-2} s^{-1} [30,31]. To determine the supplemental lighting fixtures needed, light intensity needs to be chosen. Lighting intensity is commonly between 120-200 µmol m^{-2} s^{-1} for greenhouse vegetables [32,33]. For modelling purposes, an average lighting intensity of 160 µmol m^{-2} s^{-1} will be assumed for both HPS and LED designs [34].

2.5. LIGHTING HOURS

Using the supplemental lighting DLI and PPFD are used to find the lighting hours per day as indicated in Equation III-1 [35].

$$\textbf{Lighting Hours } (hr/day) = \frac{\textbf{Supplemental Lighting DLI } \left(\frac{mol}{m^2 d^{-1}}\right)}{\textbf{PPFD} \left(\frac{umol}{m^2 s^1}\right) * \left(3600 \frac{s}{hr}\right) * \left(1x10^6 \frac{mol}{umol}\right)} \qquad \textit{(Equation III-1)}$$

Due to crop photoperiod restrictions, ideally the maximum hours the crop should be lit for is a 20-hr period [36]. Although there are studies that explore 24-hr lighting, this lighting strategy will not be considered for electricity projection ease [33,37]. Based on this restriction the average hours lit per day for each month can be found in Figure III-4.

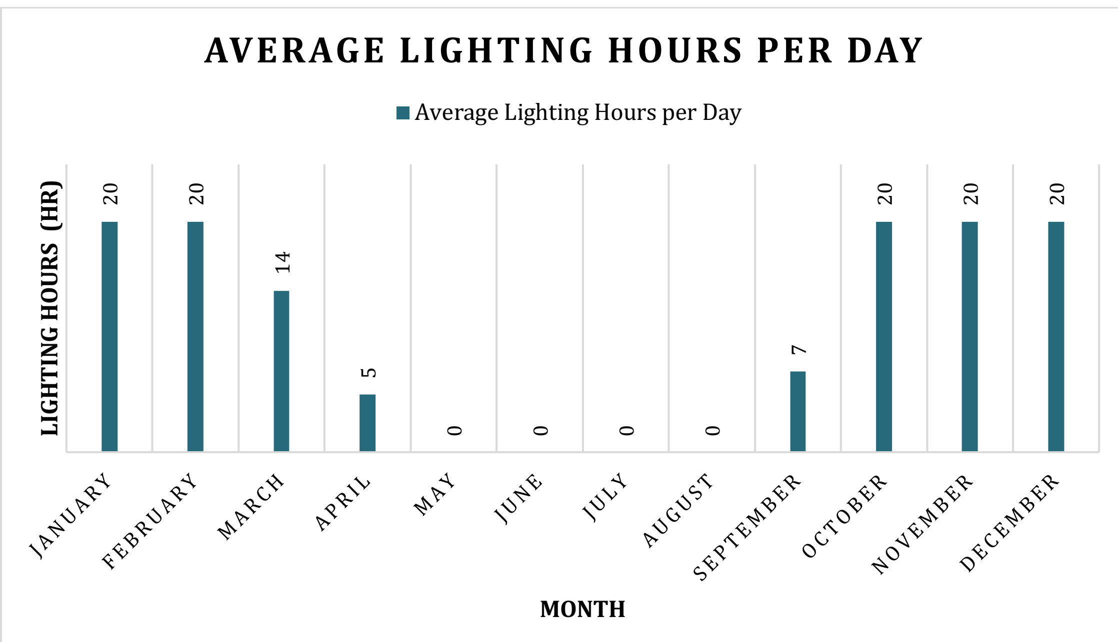

Figure III-4: Average Lighting Hours per Day

The total lit hours per month can be found in Figure III-5.

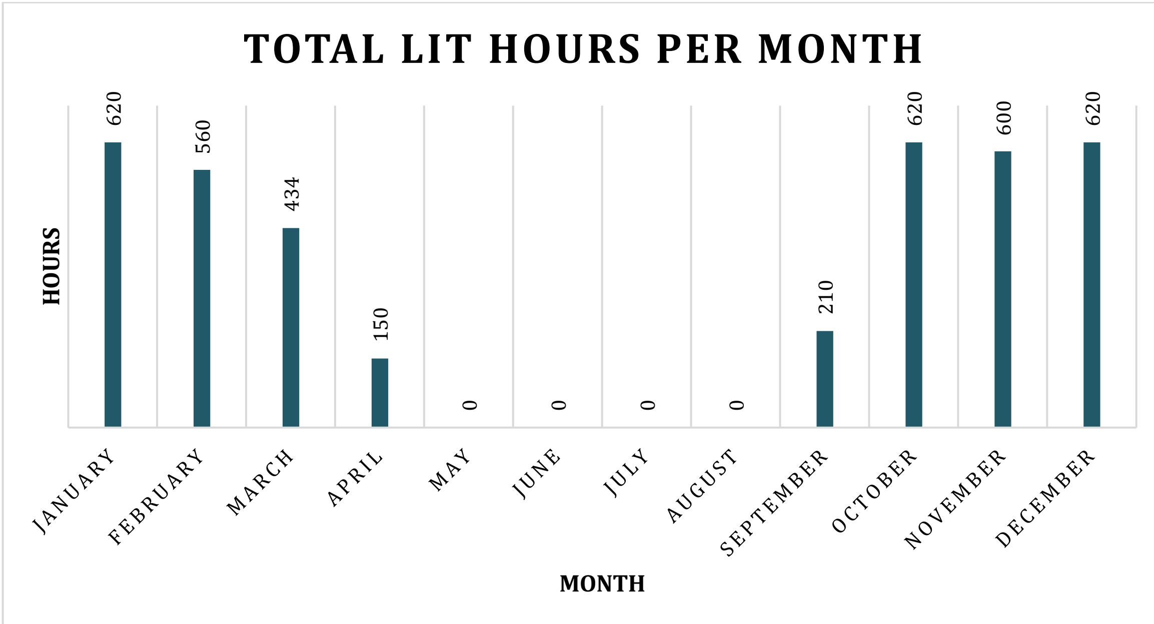

Figure III-5: Total Lit Hours per Month

2.6. LIGHTING ELECTRICAL CONSUMPTION

To determine the electricity consumption corresponding to the supplemental lighting, two HPS and one LED fixtures were chosen. Ultimately, the chosen fixtures will provide an approximate projection. Commonly, HPS lights are often installed with power 600W and 1000W [38–42]. The 600W HPS fixtures are used for older greenhouses that were designed shorter than new greenhouses to prevent the burning of crops. For LEDs, the fixture power used is 200W [39]. However, it should be noted with supplemental lighting becoming more common, a wide variety of HPS and LED fixtures are available on the market and in practice. In this case, the fixture specifications shown in Table III-2 were used for the projections [43–45].

Table III-2: Fixture Specifications

Fixture Name	Type	Power (W)	Light Output (µmol/s)
Agrolux - ALF1000	HPS	1000	2100
Agrolux - ALF600	HPS	600	1190
Philips GreenPower LED TLL	LED	200	550

To calculate the number of fixtures required to meet the lighting targets, Equation III-2 was used.

$$\boldsymbol{Number\ of\ Fixtures} = \frac{\boldsymbol{Light\ Output}\ (\boldsymbol{\mu mol/s})}{\boldsymbol{PPFD}\left(\frac{\boldsymbol{umol}}{\boldsymbol{m^2 s 1}}\right)} * \boldsymbol{Lighting\ Area}\ (\boldsymbol{m^2}) \qquad \textbf{\textit{(Equation III-2)}}$$

To calculate the total electricity demand and consumption from these fixtures, Equation III-3 and Equation III-4 were used.

$$\boldsymbol{Electricity\ Demand}\ (\boldsymbol{W}) = \boldsymbol{Number\ of\ Fixtures} * \boldsymbol{Power}\ (\boldsymbol{W}) + \boldsymbol{Base\ Load}\ (\boldsymbol{W}) \qquad \textbf{\textit{(Equation III-3)}}$$

$$\boldsymbol{Electricity\ Consumption}\ (\boldsymbol{Wh}) = (\boldsymbol{Electricity\ Demand} + \boldsymbol{Base\ Load})(\boldsymbol{W}) * \boldsymbol{Lit\ Hours}\ (\boldsymbol{h}) \qquad \textbf{\textit{(Equation III-4)}}$$

These parameters will be used to calculate the electrical capacity of the greenhouse sector.

2.7. ELECTRICAL GRID MODELLING

To apply this data modelling to the electricity grid, a few scenarios will be considered. An electricity comparison will be shown of an unlit, HPS lit, and LED lit acre. Based on the study in Chapter II, it can be approximated that the unlit crop has an electricity demand of ~12 kW/Acre and electricity consumption of ~50,000 kWh/Acre-yr. This will be used as the load for all acres without lighting and as the base load for the lit crops. For lit crops, the unlit electricity demand will be added to the electricity demand from the fixtures. The demand comparison of unlit, HPS, and LED acres can be found in Figure III-6.

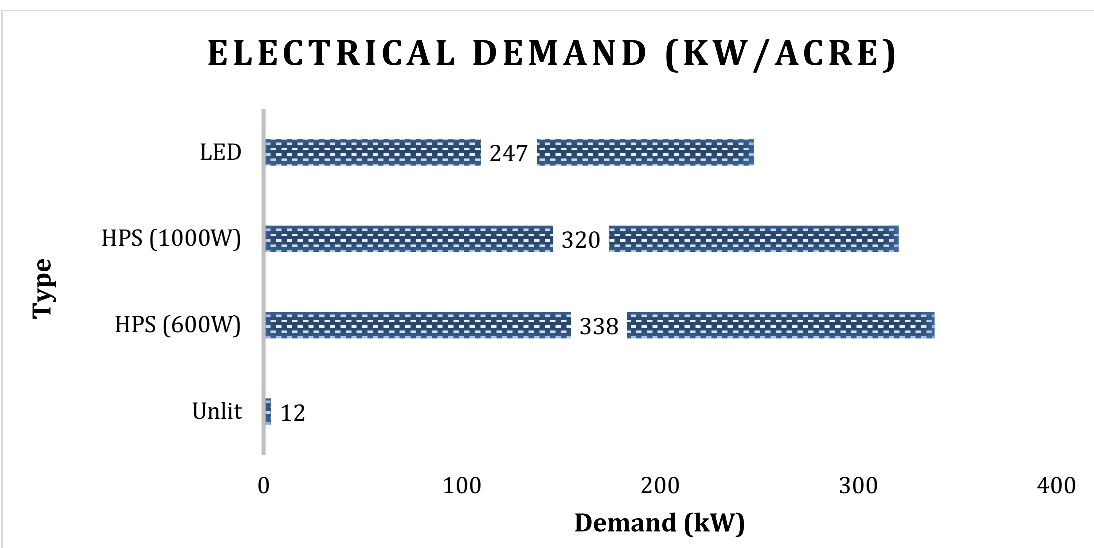

Figure III-6: Electrical Demand by Type (kW/Acre)

To demonstrate the electrical demand of the vegetable greenhouse industry on the electricity grid, an average of the HPS 600W and 1000W electrical demand will be used as the HPS acre, and the LED and unlit acre demands will be taken as is. The electrical demand based on the 2021 greenhouse sector can be shown in Figure III-7.

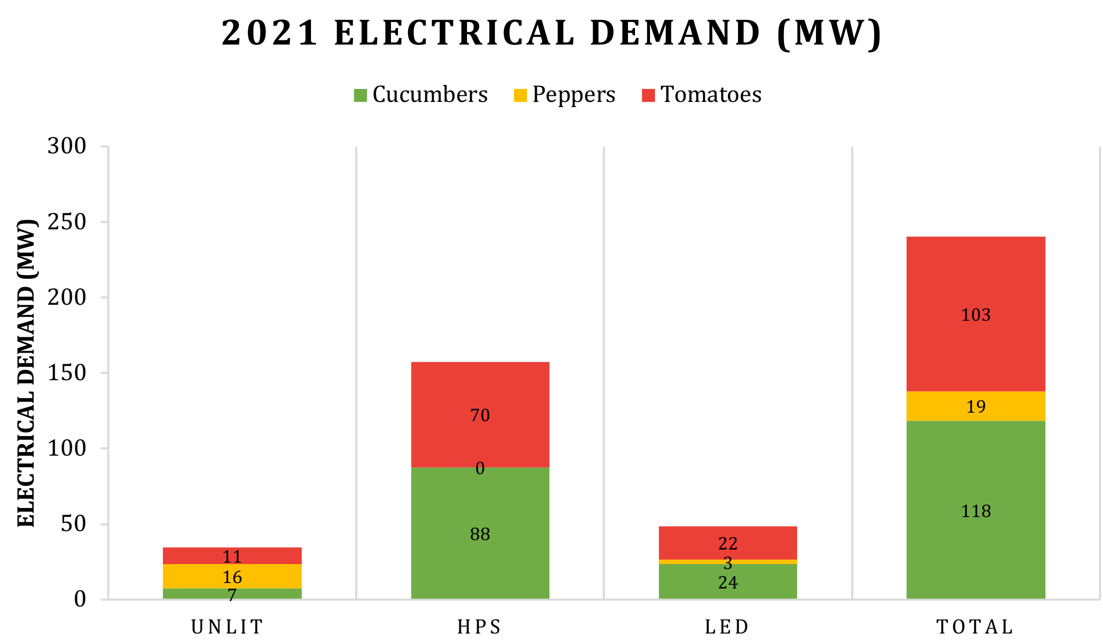

Figure III-7: 2021 Greenhouse Vegetable Electrical Demand (MW)

The electrical consumption based on the 2021 greenhouse sector can be shown in Figure III- 8.

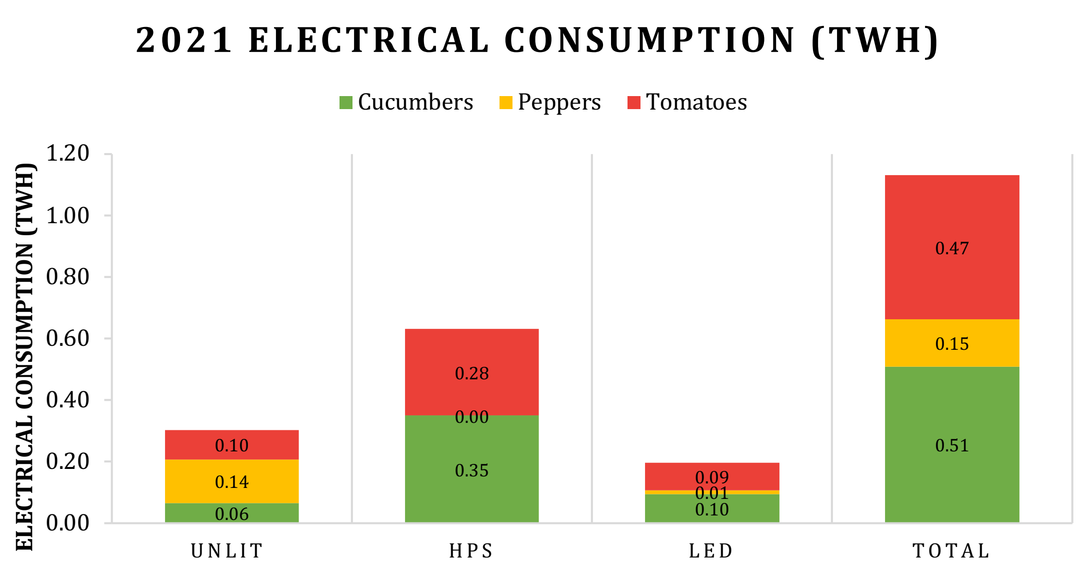

Figure III-8: 2021 Greenhouse Vegetable Electrical Consumption (TWh)

Overall, based on the approximations, the 2021 greenhouse vegetable sector has a total demand of 239 MW and a consumption of 1.13 TWh.

2.8. ELECTRICAL GRID PROJECTIONS

First, to model the impact of lighting intensity on demand and consumption, the status will be modelled with an increase of light intensity by 25%, at 200 $\mu mol\ m^{-2}\ s^{-1}$, and a decrease of light intensity by 25%, at 120 $\mu mol\ m^{-2}\ s^{-1}$ shown as scenario #1.1 and scenario #1.2 respectively.

Next, the sector will be modelled with three additional supplemental lighting combinations. One will demonstrate the consumption if the lit greenhouses are divided evenly between HPS and LEDs. The second will demonstrate the consumption if all greenhouses that add lighting after 2021 are LEDs. The third will demonstrate the consumption if, by 2030 all greenhouses with lighting have LEDs. These lighting combinations will be analyzed with the current sector acreage as well as with a sector projection. The sector will be analyzed with and without harvesting area growth projections. For sector growth projections, the average harvesting area increase will be assumed as 4.5% per year [1]. For sector lighting projections, it was assumed that by 2030, 75% of the sector will use lighting. The unlit sector will be predicted by scaling the current makeup of unlit cucumbers, tomatoes, and peppers and applying that ratio to the 25% of unlit acres. The assumption is that only 5% of cucumbers, 12% of peppers, and 8% of tomatoes remain unlit. Based on these projections, the total acreage would be 5277 acres with 3957 acres using lighting. The breakdown by crop can be found in Figure III-9.

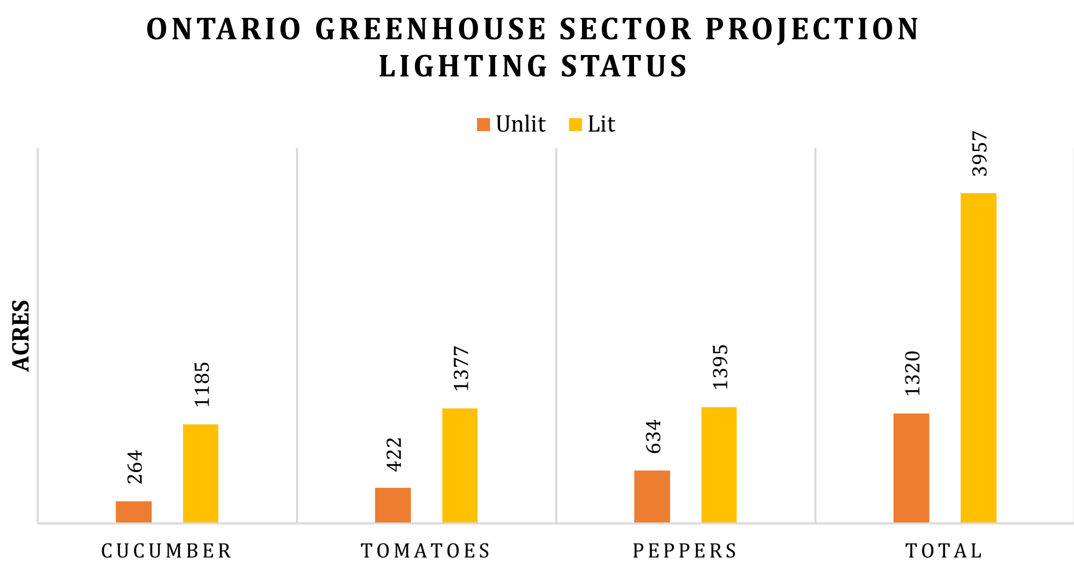

Figure III-9: Lighting Status Projections

A summary of the scenarios can be found in Table III-3.

Table III-3: Summary of Scenarios

	Lighting Splits	Lighting Intensity	Sector Projection
Scenario #1.1	Current Status	120 µmol m^{-2} s^{-1}	No
Scenario #1.2	Current Status	200 µmol m^{-2} s^{-1}	No
Scenario #2.1	50% HPS/50% LEDs	160 µmol m^{-2} s^{-1}	No
Scenario #2.2	2021 HPS/2022+ LEDs	160 µmol m^{-2} s^{-1}	No
Scenario #2.3	100% LEDs	160 µmol m^{-2} s^{-1}	No
Scenario #3.1	50% HPS/50% LEDs	160 µmol m^{-2} s^{-1}	Yes
Scenario #3.2	2021 HPS/2022+ LEDs	160 µmol m^{-2} s^{-1}	Yes
Scenario #3.3	100% LEDs	160 µmol m^{-2} s^{-1}	Yes

3. RESULTS AND DISCUSSION

The following sections detail the modelling results including lighting intensity (Section 3.1), lighting combinations on the current sector (Section 3.2), and lighting combinations on the projected sector (Section 3.3).

3.1. LIGHTING INTENSITY RESULTS

The lighting intensity demand (MW) and consumption (TWh) results for scenario #1.1 and #1.2 can be found in Table III-4 with the breakdown of the results shown in Figure III-10 and III-11. By normalizing the current sector, a demand and consumption multiplier for these scenarios is shown in Figure III-12.

Table III-4: Lighting Intensity Results

	Demand (MW)	Consumption (TWh)
Current Sector	239	1.13
Scenario #1.1	192	0.94
Scenario #1.2	291	1.32

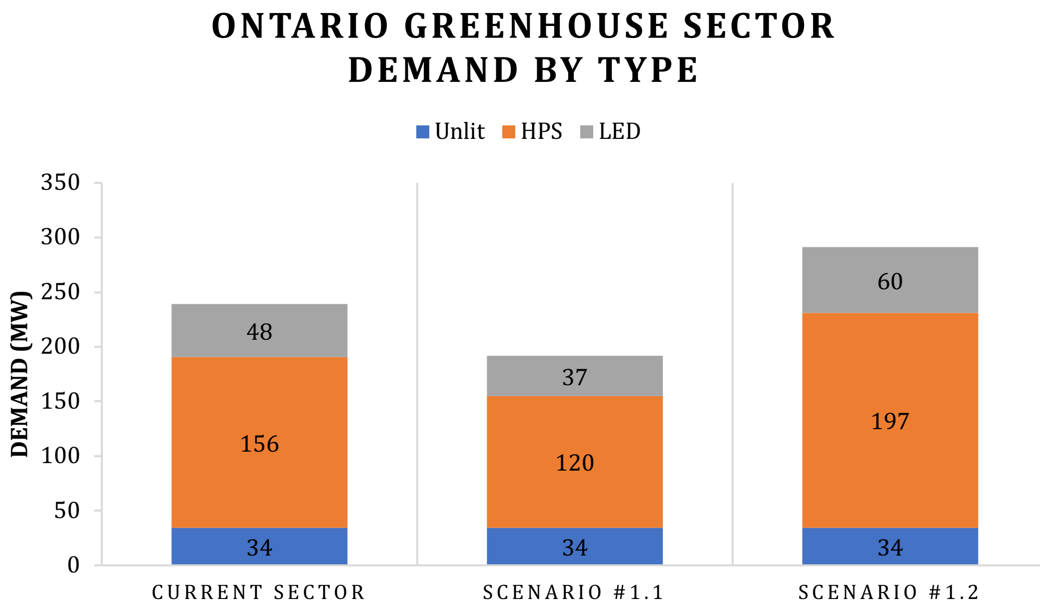

Figure III-10: Demand by Type

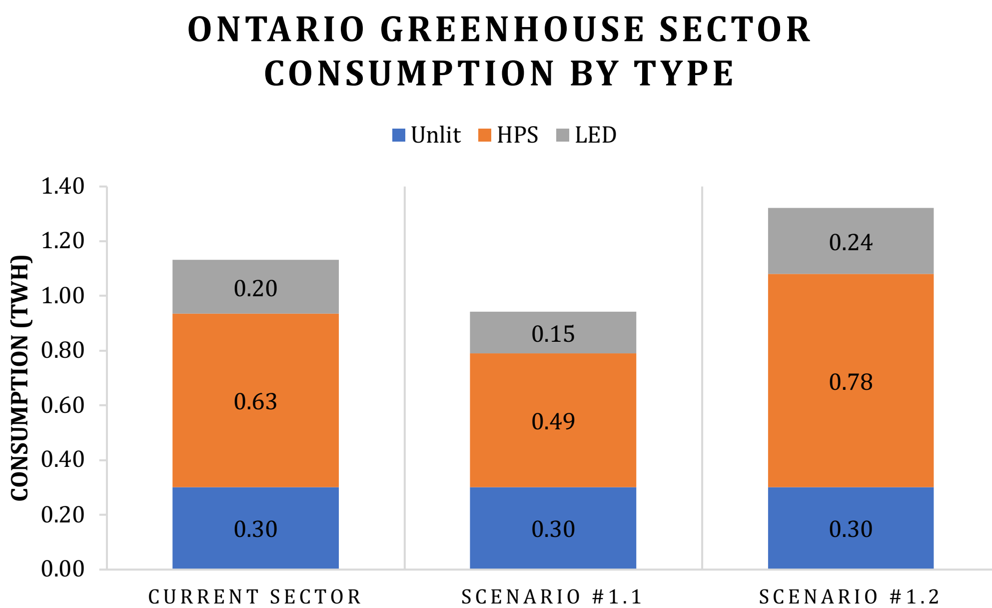

Figure III-11: Consumption by Type

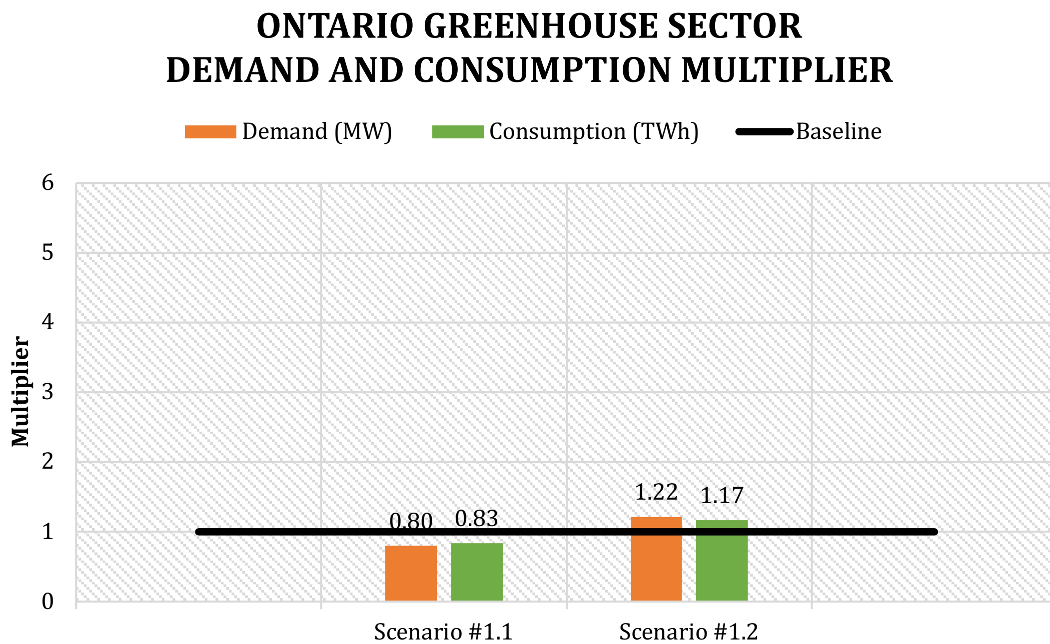

Figure III-12: Electricity Demand and Consumption Lighting Intensity Projections

As shown in scenarios #1.1 and #1.2, by decreasing or increasing the average lighting intensity used in the province by 25%, this can decrease or increase the current sectors demand and consumption. In this case, the fluctuation of lighting intensity can vary the demand by ~50 MW. Displayed in Figure III-12, this means the sectors demand can be significantly impacted by ~20% of the current electricity demand. For every 1% decrease or increase in lighting intensity on the current sector, there is approximately a correlated 0.74% impact on the grids demand. By decreasing or increasing the average lighting intensity used in the province by 25%, this can decrease or increase the current sectors consumption by 0.19 TWh. The sectors consumption is influenced by 17%. This draws the conclusion that for every 1% decrease or increase in lighting intensity on the current sector, there is approximately a correlated 0.68% impact on the grids consumption.

In Figures III-10 and III-11, it is displayed that regardless of lighting type, the impact of lighting intensity influences the electrical trends of both HPS and LED almost identically. These results prove that regardless of whether the lighting used is HPS or LED, lighting intensity has a primary impact on the electricity consumption. Ultimately, this means that the average lighting intensity of the sector can have an influential role on the electricity grid. This backs the importance of industry research when comparing lighting intensity and yield. If increased lighting intensity past a certain point does not provide a significant increase in yield and creates a strained impact on the electricity grid, there could be the potential to deny the connection request due to the inefficiency. The result from this modelling presents the future opportunity for electrical grid and utility regulation on grid connection applications based on the installed lighting intensity.

3.2. LIGHTING COMBINATIONS – CURRENT SECTOR

Based on the lighting scenarios, the demand (MW) and consumption (TWh) for scenarios #2.1, #2.2, and #2.3 can be found in Table III-5. By normalizing the current sector, a demand and consumption multiplier for these scenarios is shown in Figure III-13.

Table III-5: Current Sector Lighting Split Results

	Demand (MW)	Consumption (TWh)
Current Sector	239	1.13
Scenario #2.1	935	3.78
Scenario #2.2	842	3.42
Scenario #2.3	803	3.28

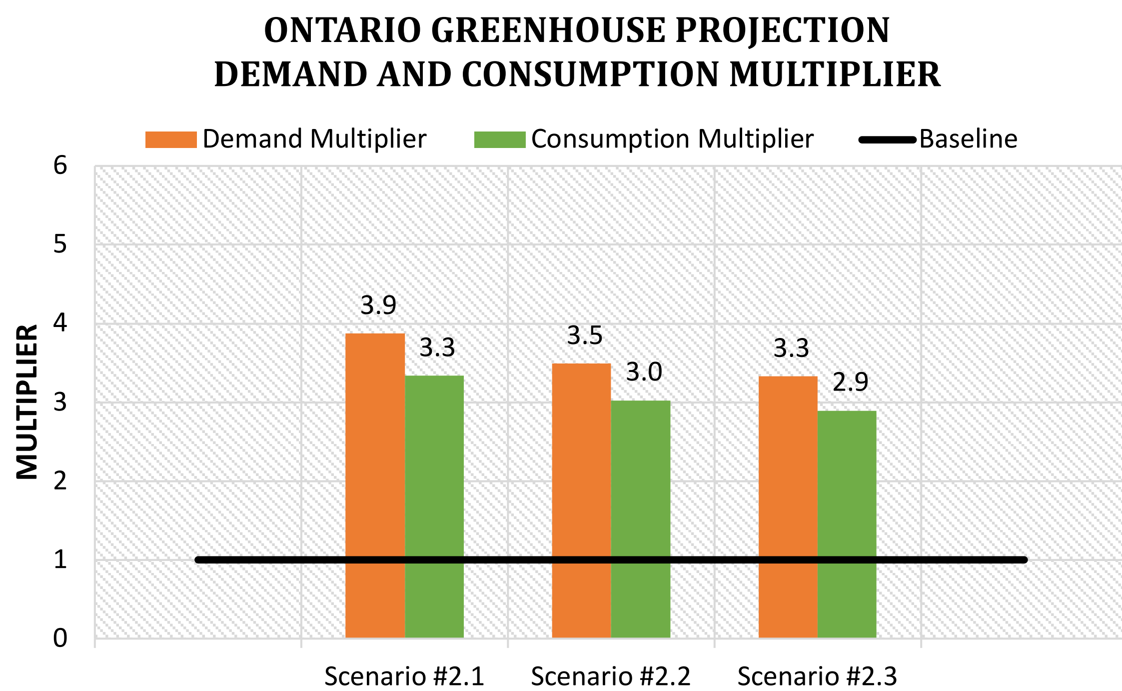

Figure III-13: Current Sector Electricity Demand and Consumption Multiplier

As shown in the projection in Figure III-13, regardless of what the lighting split is, if the sector becomes 75% lit, the electrical grid demand and consumption will increase by 3x in comparison to the 2021 sector. The modelling shows that the addition of lighting can lead the greenhouse vegetable sector in Ontario to consume over 3 TWh/year with demands ranging between 800 to 950 MW. However, technology does play a key role in reducing demand. If the entire sector used LEDs, the demand could be decreased by 130 MW and consumption by 0.5 TWh per year relative to a sector that is equally split by HPS and LEDs.

Although LED lighting technology can provide some significant relief to the grid, if the majority of the sector turned on lights, the demand and consumption would triple what it was in 2021. In comparison to the 2019 IESO Greenhouse Energy Profile Study, the projected consumption of the entire greenhouse industry could end up being the size of the vegetable sector alone. The sector was predicted to increase to 1.81 TWh in 2024 but based on this modelling it can easily be doubled if more greenhouses are given the approval to power on lights.

3.3. LIGHTING SPLITS – PROJECTED SECTOR

Based on the lighting split scenario and sector expansion projections, the demand (MW) and consumption (TWh) for scenarios #3.1, #3.2, and #3.3 can be found in Table III-6. By normalizing the current sector, a demand and consumption multiplier for these scenarios is shown in Figure III-14.

Table III-6: Projected Sector Lighting Split Results

	Total Demand (MW)	**Total Consumption (TWh)**
Current Sector	239	1.13
Scenario #3.1	1157	4.73
Scenario #3.2	1034	4.26
Scenario #3.3	982	4.05

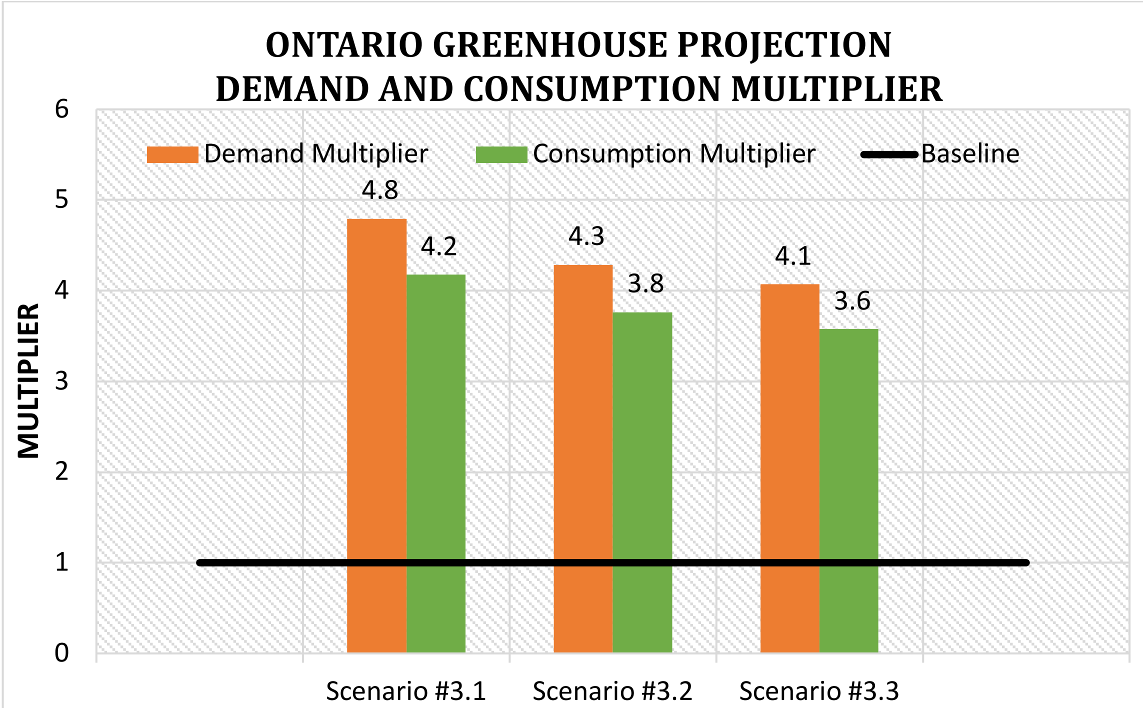

Figure III-14: Projected Sector Electricity Demand and Consumption Multiplier

As shown in Figure III-14, in comparison to scenarios #2.1, #2.2, and #2.3, the sectors projection adds around 200 MW in demand and just under 1 TWh/year. With projections and majority of the sector under lighting, the electricity grid could face ~4.4x an increase in demand and ~4x increase in consumption compared to the sector in 2021.

An interesting outcome is that the projected sector with an addition of 1726 acres and a lit sector operating LEDS as shown in scenario #3.3, closely resembles scenario #2.1. This emphasizes that although these projections with lighting show a stark contrast to the current consumption and demand, adapting electrically efficient technologies are beneficial to optimizing electricity and allowing more acres to add supplemental lighting.

4. CONCLUSION

Continued growth of the greenhouse vegetable sector is essential to ensure food security and consumer demands are met. Supplemental lighting and harvesting area expansion allows for more yield of produce but also increases the need for electricity availability. The analysis of the Ontario greenhouse vegetable sector turning towards lighting and expansion provides data driven projections on the demands the electricity grid will face. By exploring lighting intensities, lighting splits, and expansion projections, electricity operators and policy makers globally can better focus on key influences on power consumption. As more greenhouses look to turn on lights in their greenhouse, the understanding and optimizing of potential loads are critical for both the electricity and greenhouse sector.

Based on the results of this study, the following conclusions can be made on lighting intensity, electricity demand, electricity consumption, grid impact, and growth projections of a majority lit vegetable greenhouse sector in Ontario.

When compared to the electricity consumption and demand of an average lighting intensity of 160 $\mu mol\ m^{-2}\ s^{-1}$, if the 2021 vegetable sector had:

1. A decrease or increase in lighting intensity by 25%, the sectors demand would correspondingly decrease or increase by around 50 MW.
2. A decrease or increase of 1% in lighting intensity, a correlated 0.74% decrease or increase would occur to demand.
3. A decrease or increase in lighting intensity by 25%, the sectors demand would correspondingly decrease or increase by 0.19 TWh per year.
4. A decrease or increase of 1% in lighting intensity, a correlated 0.68% decrease or increase would occur to yearly consumption.

When compared to the 2021 Ontario greenhouse vegetable sector with 19% lighting, increasing the sectors lighting to 75% resulted in:

1. An electrical grid demand and consumption three folds the one approximated in 2021.
2. A demand ranging between 800-950 MW and an annual consumption of over 3 TWh per year.
3. A savings of 130 MW and 0.15 TWh per year if the sector was fully LEDs in comparison to a HPS and LED split.

When compared to the 2021 Ontario greenhouse vegetable sector, increasing the sectors lighting to 75% and the harvesting area by 1.5x resulted in:

1. An electrical grid demand and consumption four times the one approximated in 2021.
2. A demand around 1000 MW and an annual consumption of over 4 TWh per year.

Though this study is based on Ontario data, the influence of lighting intensity, lighting adaptation rates, and projection rates can be broadly applied. The specific electrical demand and consumption values are Ontario based. This application of lighting adaptation and harvesting area growth can be used as a projection tool and guide for Ontario's greenhouse sector and others.

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CHAPTER IV MODELLING A FIVE GREENHOUSE NETWORK IN ONTARIO WITH DISTRIBUTED ENERGY RESOURCE DESIGNS

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1. INTRODUCTION

The commercial greenhouse vegetable industry represents a rapidly growing sector in Canada [1]. In 2019, Ontario represented 69% of the total production in Canada with the Windsor-Essex area accounting for 60% of the operations [1,2]. Greenhouses use several commodities including electricity to power the greenhouse, natural gas (NG) to heat, and water for heat and plant growth purposes [3–5]. These commodities are typically purchased from local utilities. In Canada, some locations operate for eight months opting to remain closed during peak utility pricing periods where use of supplemental lighting and heating demand would be required to sustain crop health and production [6,7]. However, many studies indicate greenhouses should pursue year-round local production to avoid future food shortages and provide self-sufficient food economies [2,8–13]. A barrier for many operations is the high costs and lack of electricity. To meet growing food demand, it is crucial to investigate the impact and availability of electricity that comes with the innovation of a year-round greenhouse sector.

A greenhouse's electricity consumption depends heavily on the crop type, greenhouse material, operational settings, and location [6]. Major energy consumption (electricity and heating) in a greenhouse consists of supplemental lighting, heating, fans, irrigation, and more [14,15]. For greenhouses who opt for year-round production, electricity demand from supplemental lights and heating demand is a priority in the winter months [16]. The addition of supplemental lighting can increase a greenhouses electricity demand and consumption by up to 27x and 15x respectively. With greenhouses operating in a concentrated area, the cumulative impacts of expansions and the adoption of energy intensive practices will create a strain on local electricity systems.

In 2019, the Independent Electricity Sector of Ontario (IESO) stated they expected a 180% increase in greenhouse electricity consumption in five years, projecting a 282% increased use of electricity in the vegetable sector [17]. In the Windsor-Essex and Chatham Kent area, utilities are expected to quadruple the amount of power supply in the next fifteen years to meet these greenhouse load demands [18]. Although utility power expansions are planned to meet the growth, they are time intensive, requiring greenhouses to investigate quicker solutions to meet the sectors current growing pace and electricity needs.

Distributed energy resources (DERs) offer nimble and scalable options to compensate for electric grid supply shortages. DERs provide greenhouses with the ability to self-generate their electricity, heat, and CO_2 depending on the system. DERs for greenhouses can include solar, wind, cogeneration, batteries, biomass, and geothermal [19,20]. Cogeneration is a common energy choice in the greenhouse industry as these systems take fuel input and output CO_2, electricity, and heat [16,21]. In an optimized system, the CO_2 can be used as food for the crop, the heat is used to warm the greenhouses instead of the traditional boiler, and electricity is used to power the growing process.

Due to the function of cogeneration systems, they are often implemented and studied in the greenhouse space [22]. In a European study, cogeneration systems for greenhouses were found to be a cost-effective solution especially in the Mediterranean countries [23,24]. A study in Greece found that cogeneration systems for cucumber and tomato greenhouses led to increased energy savings [16]. A study in Italy found that a NG cogeneration system used 55% less energy in a tomato greenhouse compared to the heat supply from NG and canola oil combustion. Cogeneration systems are also common in Dutch greenhouses, ranging from 0.5 MW to 5MW in size [25]. In Canadian greenhouses, natural gas (NG) is the common fuel used for meeting CO_2 and heating demands [26]. Overall, cogeneration systems considered a feasible energy generation choice in the greenhouse industry.

The purpose of this study is to evaluate how DER capacity can be optimized in the greenhouse sector when designed as a microgrid with collaborating, nearby facilities in Ontario. To do so, first a detailed electricity load analysis and profiling for five greenhouses will be completed. These greenhouses vary in size, crop, lighting, and growing cycle to capture the diversity of the sector. Following this analysis, the five greenhouses electrical load will be combined to create a five-grower microgrid network and a total load analysis will be generated. Using the software Homer Pro, cogeneration designs will initially be computed for the five greenhouses individually. Then, the same design will be completed for the five-grower network. After this analysis, the five DER designs from the individual greenhouses will be totaled and compared to the five-grower network to analyze the potential reduction on capital costs and total power capacity requirements.

2. METHOD

To establish a five-grower network, five greenhouses from the same area in southwestern Ontario were chosen. These vegetable greenhouses include cucumber, tomatoes, and pepper crop with various planting and lighting cycles to accurately capture the diverse sector. This network totals 124 acres with 74 acres under HPS lighting. To complete this study, first, an electrical analysis of the five greenhouses must be complete to show the range in demand and consumption for each month in the year. This will be done per acre to normalize the data and keep the greenhouses anonymous. After understanding the individual electrical loads, the five loads will be added together to create a five-grower network. Once the electrical load is analyzed, DER designs powered by cogeneration and battery can be modelled for the five greenhouses individually and the five-grower network. This is modelled through the number and sizing of the DERs, which includes electrical and thermal yields as well as fuel consumption. A CAPEX and OPEX analysis will detail the cogenerator and battery designs capital, operating and maintenance, fuel costs, and grid purchasing. Finally, the total results of the five greenhouses individually will be analyzed alongside the five-grower network to determine if a network is a feasible route to consider.

2.1. GREENHOUSE DETAILS

The five-grower network is composed of five greenhouses located in the Leamington, ON area. The crop type and use of supplemental lighting of these greenhouses can be found in Table IV-1.

Table IV-1: Five Grower Network

Greenhouse	Crop	Supplemental Lighting
1	Pepper	Unlit
2	Pepper	Unlit
3	Cucumbers & Tomatoes	HPS
4	Cucumbers & Tomatoes	HPS
5	Long English Cucumbers	HPS

2.2. GREENHOUSE ELECTRICAL ANALYSIS

First, the five greenhouses are modelled by demand by acre as shown in Figure IV-1. The demand in this case is defined as the peak one-hour period in each month. For the unlit greenhouse loads, the demand reflects the base load which remains relatively consistent. For the lit greenhouse loads, supplemental lighting has a large impact on the overall demand of the greenhouse. This demand represents the greenhouses one hour load when they typically have all their HPS fixtures on. The demand of a lit greenhouse will increase in the winter months as more SL is needed to supplement the lack of natural sunlight for crop production whereas in the summer months natural sunlight satisfies the crops needs.

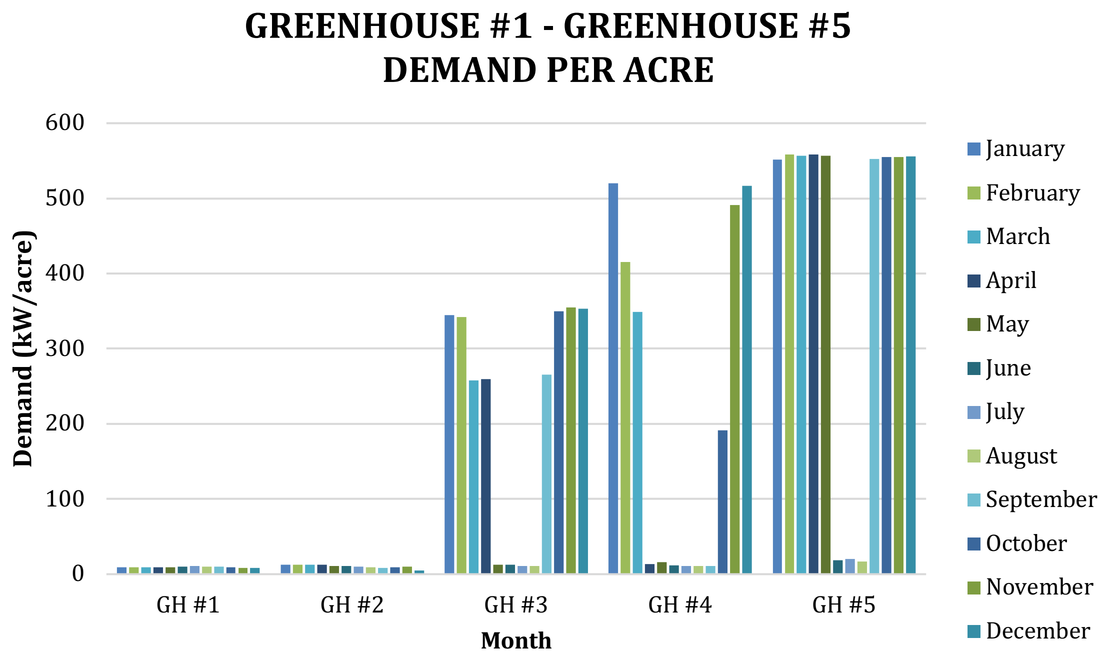

Figure IV-1: Greenhouse Maximum Demand per Acre

The five greenhouses are modelled by greenhouse average hourly electricity consumption per acre in Figure IV-2. The unlit greenhouse loads remain consistent as there are no major electrical load fluctuations. For the lit greenhouses, as the summer months are approached, the supplemental lights are used less due to an increase in DLI as the average sun per day increases. Observing the lit greenhouses, the average hourly consumption allows the differences in lighting patterns and the impact of the natural sunlight to be noticed. For instance, greenhouse #5 has a heavier lighting period and use lights extensively for nine months to boost crop yield. However, even though lighting is used for nine months, it is notable that as the DLI increases, the average hourly electrical consumption mimics this. In comparison to greenhouse #3, greenhouse #5 has a heavier monthly lighting recipe per acre. Greenhouse #5 also contrasts greenhouse #4 as they light for 3 more months. Comparing the three greenhouses, a light, moderate, and heavy lighting scenario is modelled.

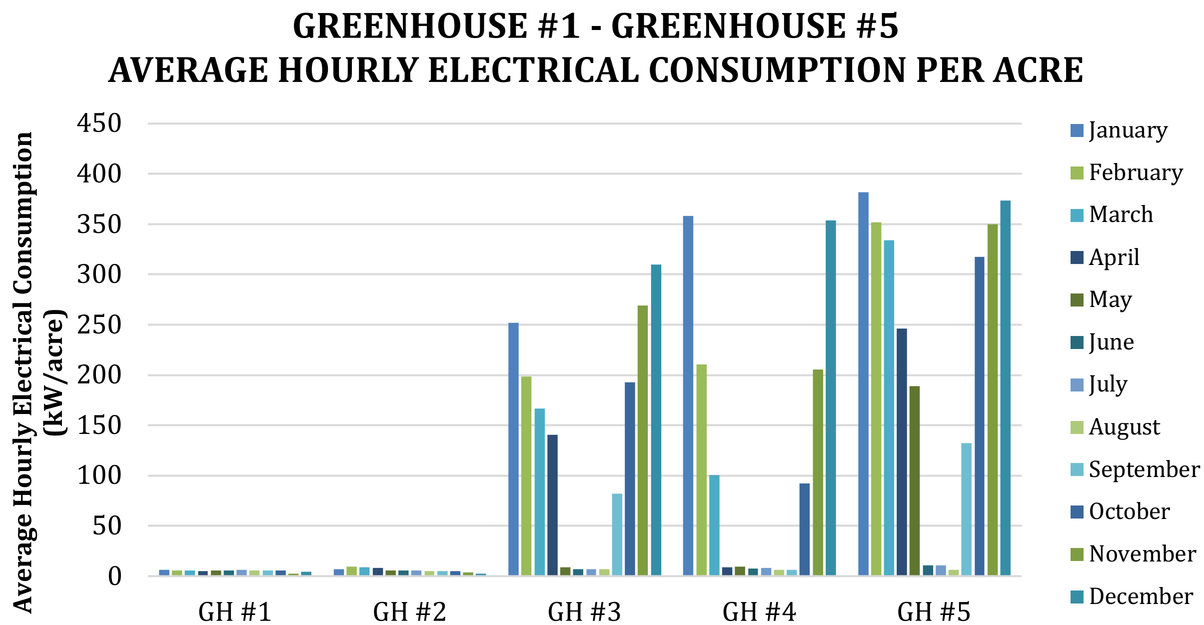

Figure IV-2: Greenhouse Average Hourly Electrical Consumption per Acre

Lastly, the monthly total electrical consumption per acre is shown in Figure IV-3. This model mimics the pattern shown in Figure IV-2. As the sun periods increase, the need for SL decreases as there is a shorter SL period. This causes higher total electrical consumption for lit greenhouses to occur in the shorter daylight months and gradually decrease as the months near May-August.

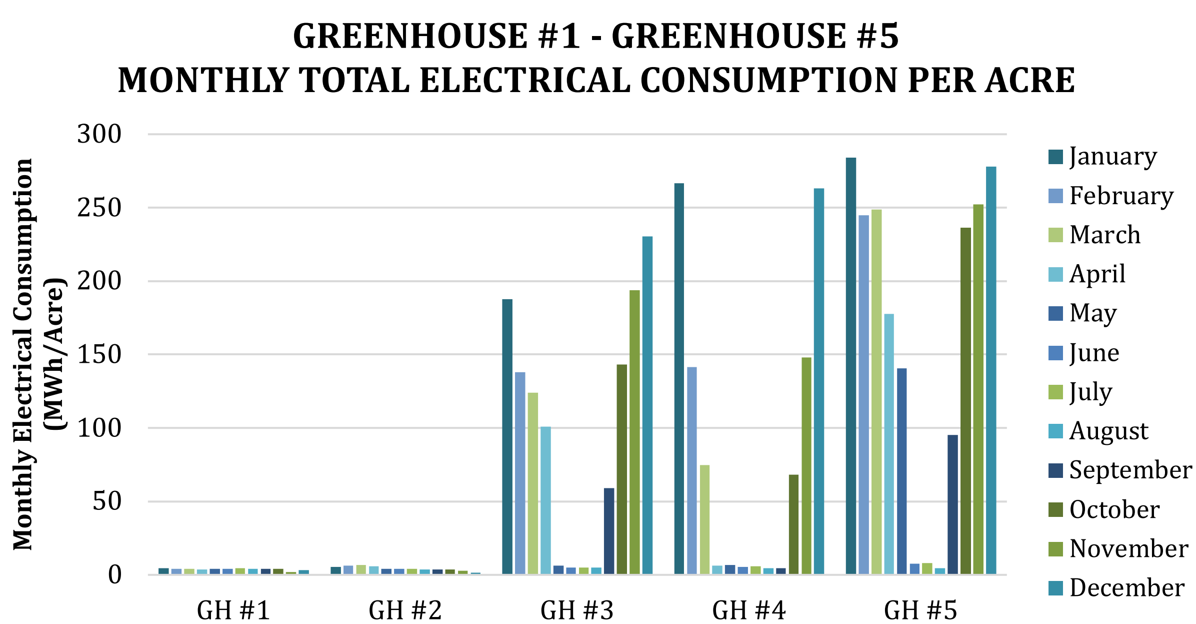

Figure IV-3: Greenhouse Monthly Total Electrical Consumption per Acre

These data points can be summarized in Table IV-2 where the maximum annual demand (kW/acre) and total annual electrical consumption (kWh/acre) are stated. The maximum annual demand is the maximum one-hour period that occurred all year. This metric is typically a crucial component in electricity billing and forecasting. The total annual electrical consumption is how much electricity was used in one year to grow one acre of the crop.

Table IV-2: Electrical Summary Figures

Greenhouse	Maximum Annual Demand (kW/Acre)	Total Annual Electrical Consumption (kWh/Acre)
1	11	46,899
2	13	51,830
3	355	1,199,135
4	520	996,735
5	559	1,977,416

2.3. FIVE-GROWER NETWORK ELECTRICAL ANALYSIS

Combining the five greenhouses into a five-grower network provides valuable information as it samples what 124 acres of greenhouse electrical load can look like. These 124 acres represent unlit and lit greenhouses as well as the major greenhouse vegetables cucumber, peppers, and tomatoes. In Figure IV-4, the monthly demand profile of the five-grower network can be found. In the winter months demand can reach approximately 40 MW. In the summer months, demand can be as low as approximately 1MW, which indicates that demand associated with supplemental lights can result in an ~40x increase.

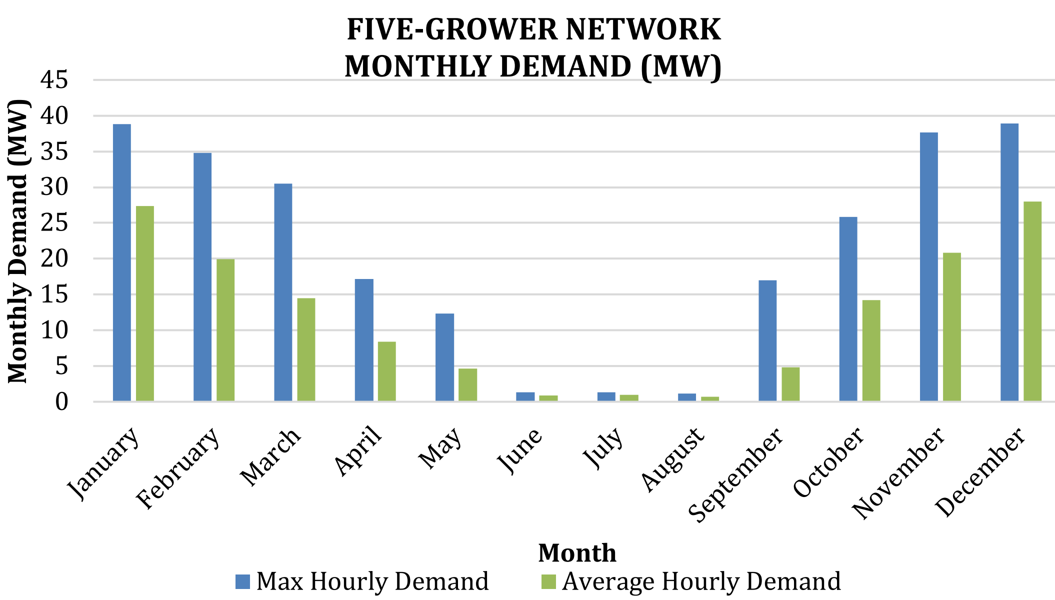

Figure IV-4: Five-Grower Network Monthly Demand (MW)

Next, in Figure IV-5 the annual average hourly profile is demonstrated. Observing this graph, from 12:00AM to 8:00AM the hourly usage peaks due to lack of sunlight, dropping at 9:00AM to 1PM as the sun begins to rise, increasing from 2:00PM to 5:00PM, then dropping from 6:00PM to 10:00PM. At 11:00PM as the lights begin to start up again for nighttime lighting, the load increases yet again.

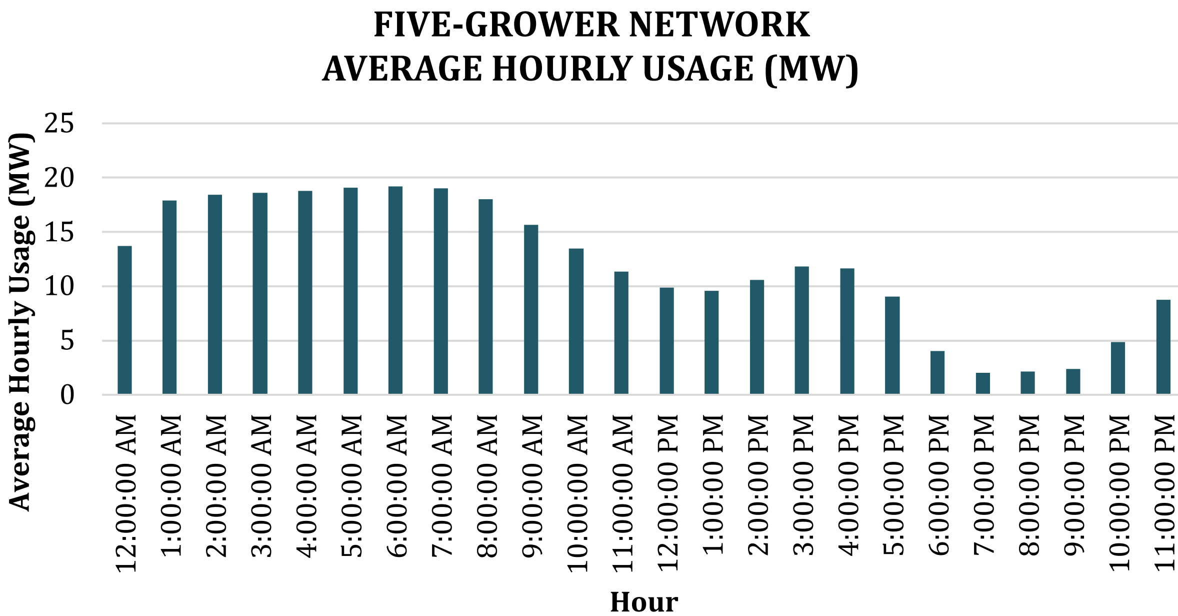

Figure IV-5: Five-Grower Network Average Hourly Usage (MW)

In Figure IV-6, the average hourly usage is demonstrated for each month. Analyzing the lighting months (January to May and September to December) there is a dip in electricity usage at 12:00PM and another dip at 6:00PM showing the periods where lighting is reduced/turned off. In June, July, and August it is shown that no supplemental lights are being used. In April, May, and September it is shown that there is less intensity of supplemental lights being used, as the daylight hours are higher in those months.

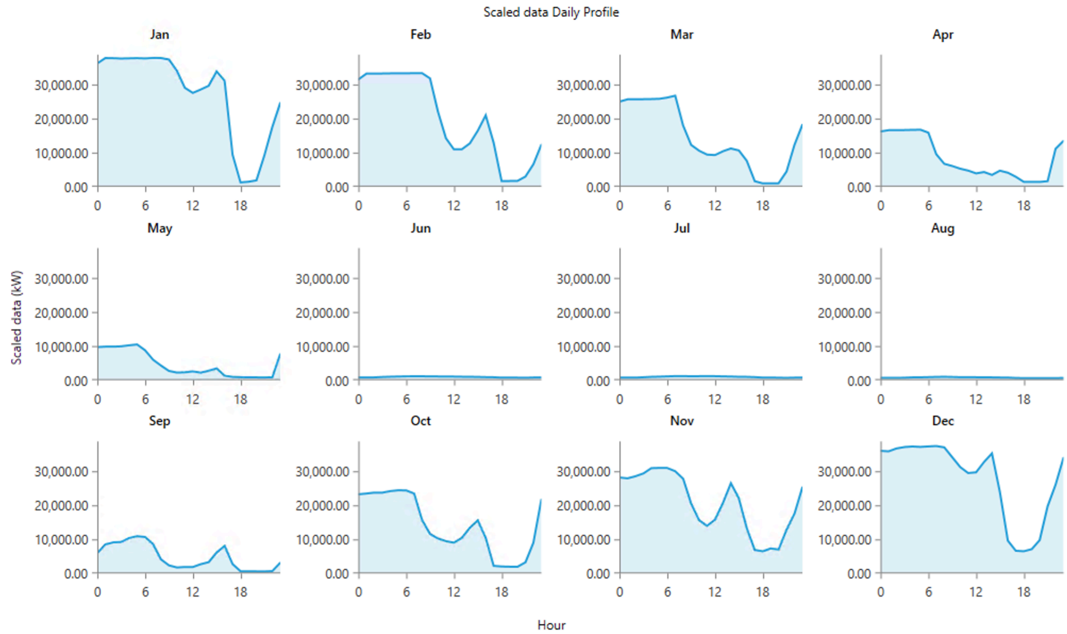

Figure IV-6: Five-Grower Network Monthly Average Hourly Usage Profile (MW)

Figure IV-7 displays the total monthly consumption for the five-grower network. There is a clear U-shaped distribution, with the lowest consumption occurring between June – August and the peaks occurring in the colder months as total monthly consumption increases due to the need for supplemental lighting. Overall, the total monthly consumption can be as high as ~20,000MWh and as low as ~550MWh, representing approximately a 36x difference.

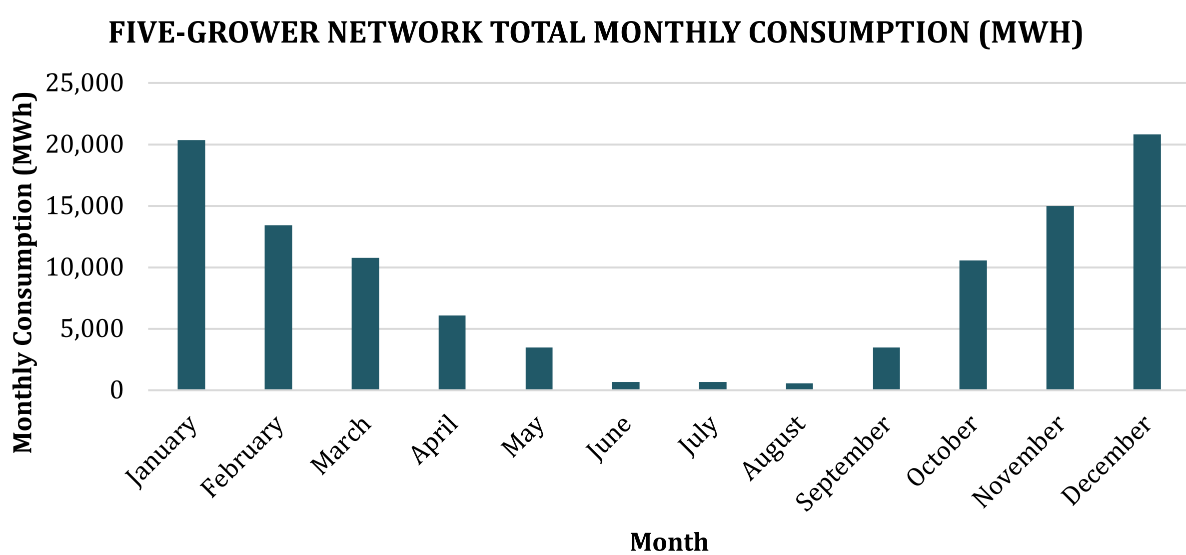

Figure IV-7: Five-Grower Network Total Monthly Consumption (MWh)

Overall, for the five-grower network the maximum annual demand is 0.314 MW/Acre and the total annual electrical consumption is 853 MWh/Acre.

2.4. COGENERATION AND BATTERY SPECIFICATIONS

The DER designs will include cogeneration, as commonly practiced for greenhouses, and a battery system to create an off-grid generation system. From industry manufacturers, specifications for the cogenerators are shown in Table IV-3. The input power in this case is the natural gas used to power the cogenerator and the output power represents both the electrical and thermal outputs.

Table IV-3: Cogenerator Specifications

Model	Input Power (kW)	Output (kW)	
		Electrical Power	Thermal Power
4 MW	9,463	4,369	4,491
1 MW	2,696	1,061	1,095

These cogenerator specifications can be further explored in Table IV-4 and Table IV-5 where the power input and output details are given when it is operating at 100%, 75%, and 50%. These data points will be used to create a fuel curve to accurately mimic the operation of the cogenerator.

Table IV-4: 1 MW Cogeneration Operation Details

	100%	75%	50%
Power Input (kW)	2,696	2,092	1,496
Thermal Output (kW)	1,095	821	548
Electrical Output (kW)	1,061	795	527

Table IV-5: 4 MW Cogeneration Operation Details

	100%	75%	50%
Power Input (kW)	9,463	7,262	5,061
Thermal Output (kW)	4,491	3,368	2,246
Electrical Output (kW)	4,369	3,266	2,159

Designing these systems as off grid solutions, battery storage is used to help assist with the power supply. In this case, a Lithium-ion battery will be used assuming an initial state of charge at 60% and a minimum state of charge as 20%.

2.5. HOMER PRO SOFTWARE

To design these DER systems, the software HOMER Pro will be used to support and validate overall design decisions. HOMER (Hybrid Optimization of Multiple Energy Resources) Pro is a DER tool that considers electrical and thermal load, location, costs, and DER assets to generate optimized designs [27]. HOMER simulates various systems using the given equipment options and uses user inputted criteria to propose optimal systems. Using these cogeneration and battery specifications, the greenhouse load profiles, and location this will be inputted into the software HOMER Pro to create DER designs will be generated to satisfy the electrical load. After completing these designs for all five greenhouses, these results will be added together and referred to as the total design result. The same DER design will be completed for the five-grower network with the intention to explore the potential reduction in the amount of DER when centralized.

From the design results, the following parameters will be analyzed: fuel consumption, electricity generation, thermal generation, and unmet electrical load. Fuel consumption is the total annual fuel used for cogeneration. Electricity generation and thermal generation are the total annual output of electrical power and thermal heat from the cogenerator. Cogenerator capacities are selected based on available industry sizing, and therefore, are not exactly sized to match greenhouse loads. For this reason, excess electricity is cogeneration power that is not used by the greenhouse. This is typically during a period when the cogenerator can actively meet the greenhouses load and the battery storage is full. Unmet electrical load is the amount of electricity the cogeneration and battery system are unable to meet. This is typically during a period when the cogenerator is not running and the battery is at minimum state of charge. This can also be the case when a lit greenhouse is using lighting and the cogenerator is not large enough to fully satisfy the full load.

2.6. CAPEX and OPEX Analysis

To complete a CAPEX analysis for the total and five-grower design, the capital costs of the cogeneration and battery systems will be used. To complete an OPEX analysis, the O&M costs for the cogenerator and battery will be considered, as well as battery replacement, fuel cost, and grid purchased electricity. The project period will begin in 2022 and a 25-year project analysis will be conducted.

Consulting with local industry experts and online forecasts the following values were used for the capital and operational costs of these assets as shown in Table IV-6. Operational costs are assumed to escalate at 5% annually. The battery is assumed to be replaced halfway through the 25-year project.

Table IV-6: Cost Analysis Parameters

CATEGORY	COST
Cogeneration Capital ($/MW)	$1,750,000
Cogeneration O&M ($/MW-yr)	$75,000
Battery Capital ($/MW) [28]	$1,380,000
Battery Replacement ($/MW) [28]	$992,000
Battery O&M ($/kW-yr) [29]	$14

The natural gas fuel costs are taken from a Deloitte forecast study using the Ontario Dawn reference point. These costs are forecasted until 2041, following that a 2% increase is assumed [30]. To estimate the carbon tax on the fuel, the carbon dioxide emission rate will be used as 1.926×10^{-3} tonne per m^3 of natural gas [31]. Carbon tax is taken as $50/tonne as of 2022 and assumed to increase $15 per year until 2030 based on federal projections [32]. As there are no federal projections of carbon tax beyond 2030, a 3% increase is assumed. The carbon tax will be shown in two scenarios: scenario one without any federal reduction and scenario two with the 80% carbon tax reduction currently in place in Ontario due to agricultural use of natural gas [33].

For the unmet electrical load, the electricity pricing purchased from the grid will be assumed as $0.13/kWh. It is assumed that electrical increases at 3% annually.

Assessing the design with the cogeneration and battery cost figures and the energy figures from the natural gas and electricity, the CAPEX and OPEX analysis will be completed. The CAPEX and OPEX analysis will be shown as a net present value with a 5% interest rate. Lastly, the cost of electricity for the designed will be completed in two scenarios. The first by taking the total project cost over the total electricity generated by the system and the second by taking the total project cost over the total electricity used by the system.

3. RESULTS AND DISCUSSION

3.1. DESIGN RESULTS

Using the HOMER Pro software, the results for the number of cogenerators, sizing, and details were generated. These results are shown in Table IV-7.

Table IV-7: Cogeneration Design Results

GREENHOUSE	NUMBER OF COGENERATOR(S)	COGENERATION SIZE (MW)	DETAILS
1	1	1.061	1 x 1.061 MW
2	1	1.061	1 x 1.061 MW
3	3	6.491	1 x 4.369 MW 2 x 1.061 MW
4	3	13.107	3 x 4.369 MW
5	3	13.107	3 x 4.369 MW
TOTAL	11	34.827	4 x 1.061 MW 7 x 4.369 MW
FIVE - GROWER	**11**	**31.519**	**5 X 1.061 MW** **6 X 4.369 MW**

By combining the five greenhouses into a five-grower network, the cogeneration size was able to decrease one 4MW cogenerator and replace it with 1MW cogenerator. This results in a 3.308 MW reduction. The summary of the cogeneration design results can be found in Figure IV-8.

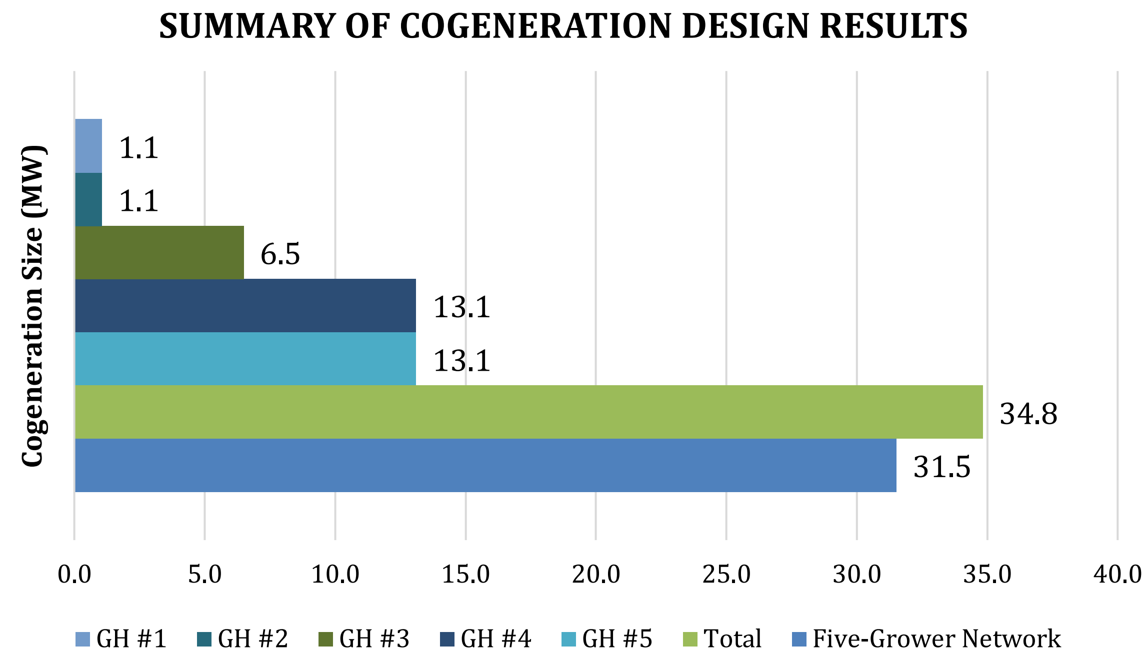

Figure IV-8: Summary of Cogeneration Design Results

To supplement the off-grid cogenerator design, the battery results can be shown in Figure IV-9. Comparing the total to the five-grower network, there is 6MW of battery savings when centralizing the greenhouses.

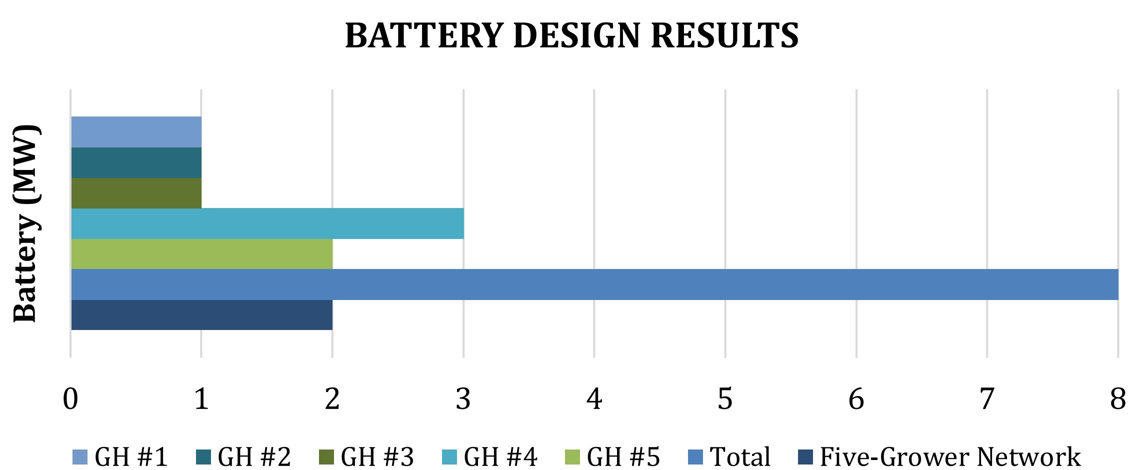

Figure IV-9: Battery Design Results

Based on these cogeneration systems, the operation results can be found in Figure IV-10 where the input fuel is shown as fuel consumption and the outputs such as thermal generation and electrical generation are shown as well. By combining the greenhouses, the system uses 12% less fuel and produces 19% less electricity and 12% less thermal generation.

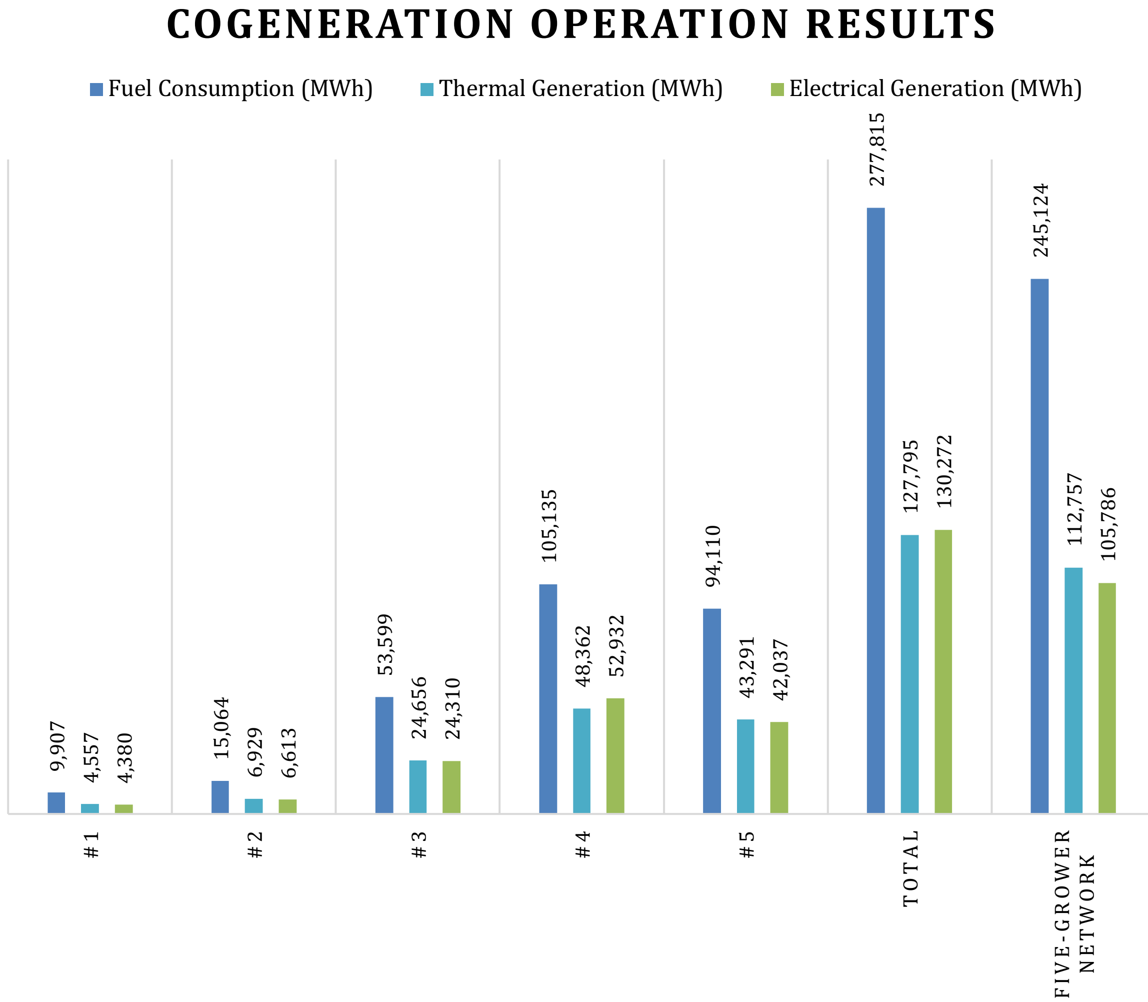

Figure IV-10: Cogeneration Operation Results

In Figure IV-11, the electricity operation results are displayed showcasing the unmet electrical load, electrical load served, and excess electricity. While the total only falls short 0.32% of the electrical load, the five-grower network falls 2.4% short. However, the five-grower network produces ~1/5 of the excess electricity the total design produces. Depending on the project location and electrical grid, an abundance of excess electricity can be seen as an issue or benefit for some systems.

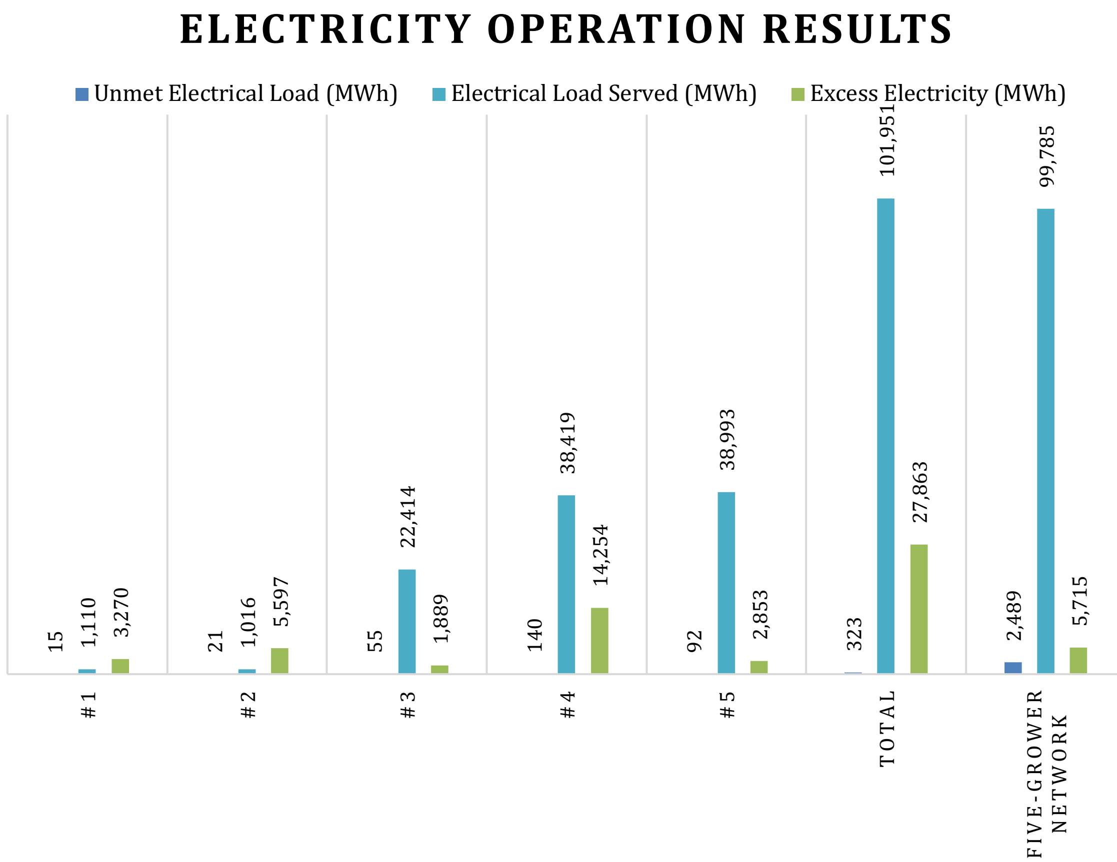

Figure IV-11: Electricity Operation Results

Overall, individual systems and a network system have different operation results that can be seen as beneficial or challenging depending on the operator.

3.2. CAPEX AND OPEX RESULTS

Applying the DER costs as well as the projected electricity and natural gas costs, the CAPEX and OPEX of these designs were completed. In Figure IV-12, the total project costs are shown with no agricultural rebate on the carbon tax. In Figure IV-15, the total project costs are shown with the agricultural rebate on the carbon tax. The agricultural rebate with the natural gas projections can reduce the fuel costs by 49%, saving these greenhouses a total of $92.8 million dollars. In these designs, cogeneration fuel is the costliest component, followed by cogeneration O&M, and cogeneration capital.

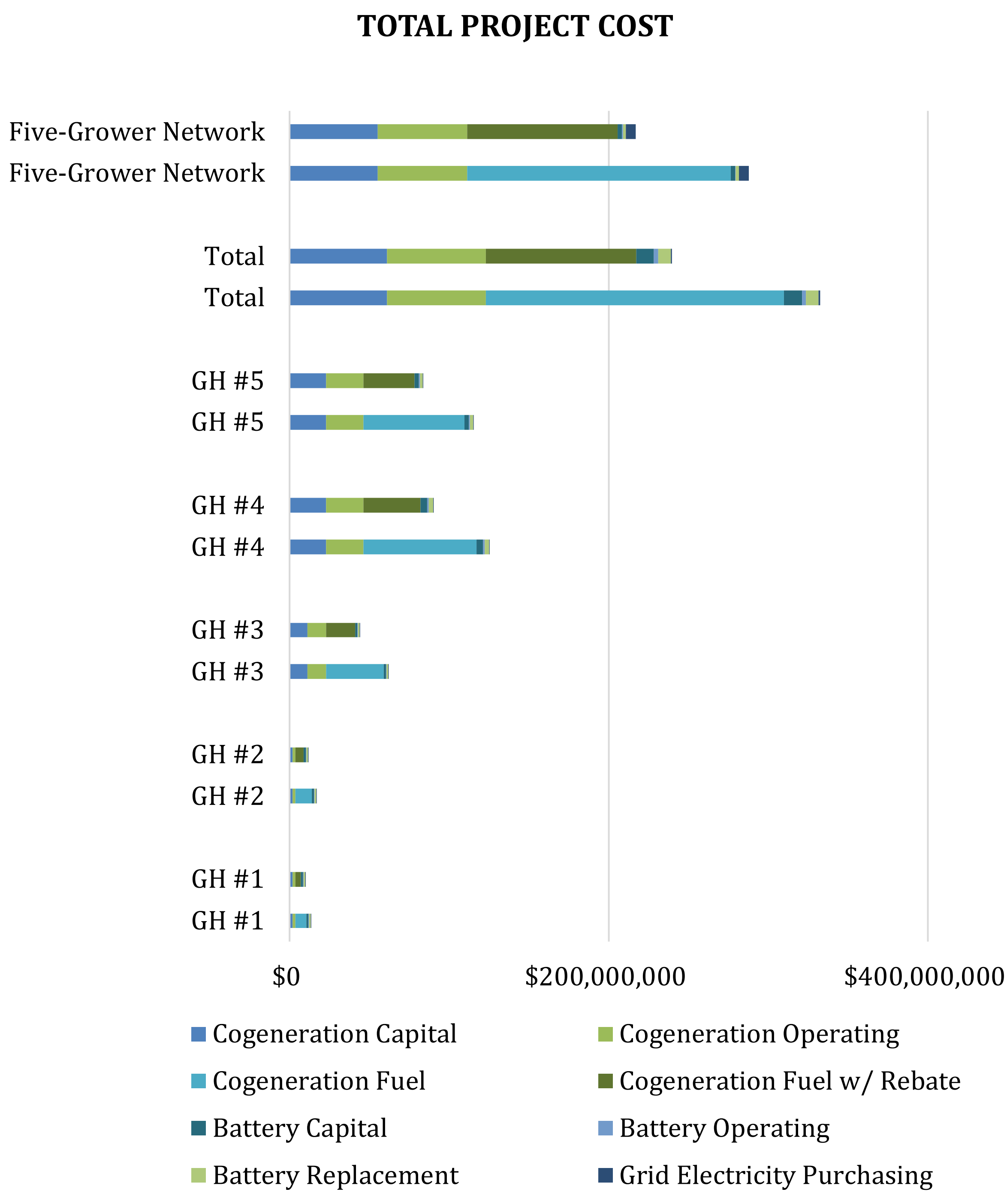

Figure IV-12: Total Project Costs

The comparison of the five individual operations versus the five-grower network can be found in Figure IV-13. By combining the greenhouses there was a 20% reduction in capital costs, 12% reduction in operational and fuel costs. However, electricity grid purchasing was 7.7x more in the five-grower network scenario. Overall, the five-grower network has a total savings of $44.5 million without the agricultural rebate and $33.6 million with the agricultural rebate.

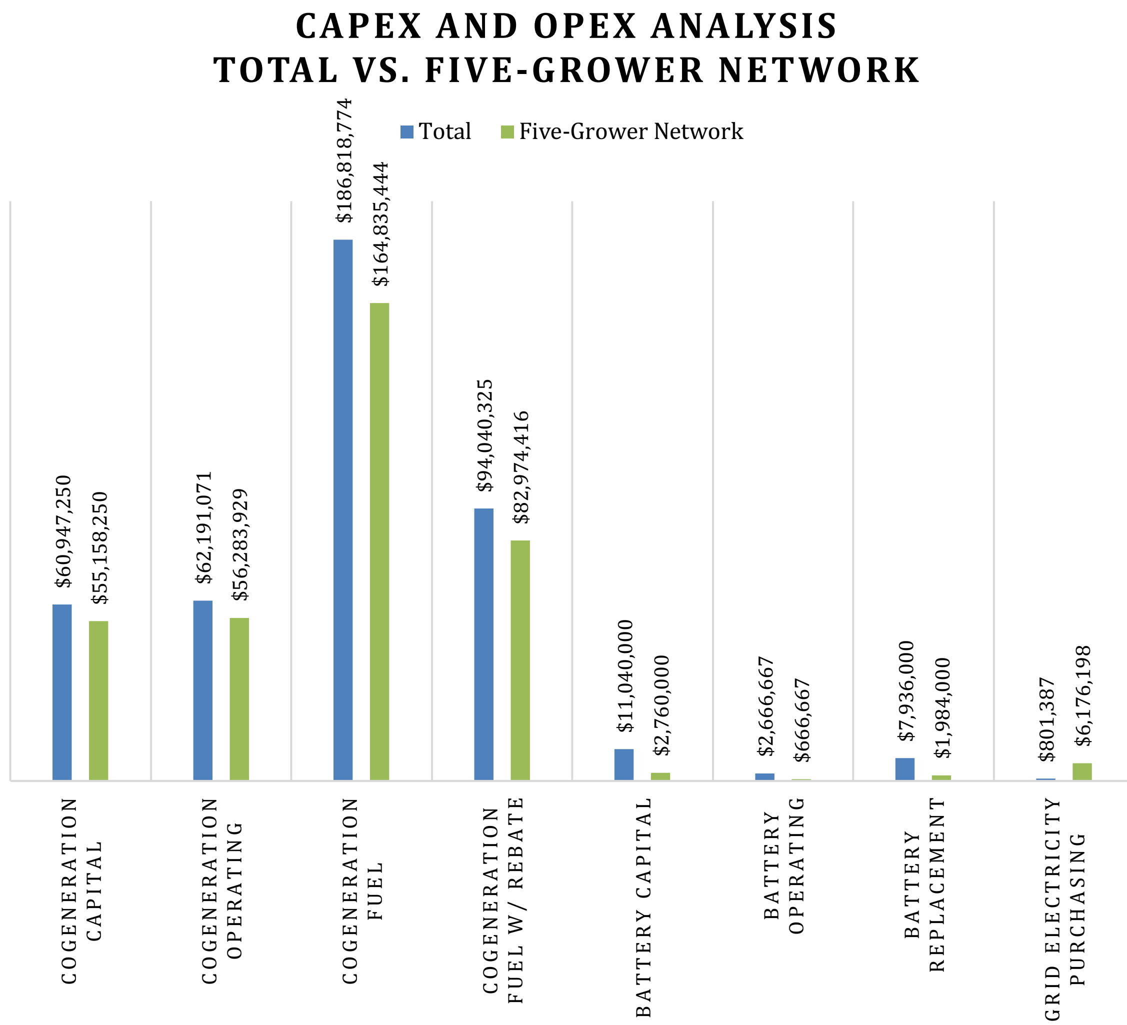

Figure IV-13: Total vs. Five Grower Network

To summarize, the cost of electricity for these cogeneration and battery designs can be found in Table IV-8 and Table IV-9. In Table IV-8, all the electricity generated is assumed to be used. In Table IV-9, the excess electricity is not included and only the electricity directly used to meet the load is considered. By calculating this way, the input fuel costs for the excess electricity is considered. This is especially important to note in the unlit greenhouses Greenhouse #1 and #2 as they have smaller electrical loads, making a 1 MW cogenerator too large for their needs. When excess electricity is not used elsewhere, the cost of electricity can be 6.5x more for smaller electrical load greenhouses.

Table IV-8: Cost of Electricity (Total Generated Electricity)

Greenhouse	Cost of Electricity ($/kWh)	Cost of Electricity w/ Agricultural Rebate ($/kWh)
#1	$0.12	$0.09
#2	$0.10	$0.07
#3	$0.10	$0.07
#4	$0.09	$0.07
#5	$0.11	$0.08
Total	$0.10	$0.08
Five-Grower Network	$0.11	$0.07

Table IV-9: Cost of Electricity (Total Electrical Load Served)

Greenhouse	Cost of Electricity ($/kWh)	Cost of Electricity w/ Agricultural Rebate ($/kWh)
#1	$0.47	$0.35
#2	$0.66	$0.46
#3	$0.11	$0.08
#4	$0.13	$0.09
#5	$0.12	$0.09
Total	$0.13	$0.09
Five-Grower Network	$0.12	$0.08

4. CONCLUSION

Distributed Energy Resources are a feasible option to enable the growth and independence of the greenhouse sector in Ontario when local electricity grid and utilities are unable to match the demand. The addition of DERs allows greenhouses to pursue expansion and innovative technology adoption without concerns of electricity approval and delay. The analysis of a five-grower network in Ontario provides an electrical data load example of over one hundred acres of greenhouses with various vegetable crops and lighting habits. Through the electrical data analysis of the five greenhouses, the following conclusions can be made:

- The electrical demands in the summer months can be up to ~40x less than the winter months
- Annually, total monthly consumption can vary by ~36x throughout the year
- Overall, based on the five greenhouses, there is a maximum annual demand of 0.314 MW/acre and a total annual electrical consumption of 853 MWh/acre

By assessing a cogeneration and battery system on these greenhouses, the following conclusions on a five-grower network can be made:

- By creating a network, 3.308 MW of cogeneration and 6MW of battery can be reduced
- A five-grower network uses 12% less fuel and produces 19% less electricity and 12% less thermal generation in comparison to a decentralized design
- There is a load electrical shortage of 0.32% for the total design and a 2.4% for the five-grower design. In comparison to the total design, the five-grower network produces ~1/5 of the excess electricity.
- The five-grower network has a 20% reduction in capital costs, 12% reduction in operational and fuel costs, and 7.7x increase in electricity grid purchasing.
- Comparing the designs with and without the agricultural rebate, the rebate can reduce the fuel costs by 49% creating savings up to $92.8 million dollars.
- The five-grower network has a total savings of up to $44.5 million dollars
- When excess electricity is not used elsewhere, the cost of electricity can be 6.5x more for smaller electrical load greenhouses.

Although this study is based in Ontario, the key design results can be used internationally. This design analysis can be used for greenhouses to explore self-generation options when met with issues like grid shortages.

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CHAPTER V CONCLUSION

SUMMARY AND CONCLUSIONS

Significant innovations are being made in the greenhouse sector to meet the growing food demand, resulting in increased electricity consumption. However, many studies surrounding innovative supplemental lighting rarely consider the overall impact the technology has to the electrical grid. The increase of power usage creates concerns for local grids that lack the infrastructure to support this rapid uptake. Therefore, this work provides notable analysis by representing priorities of both the electricity and greenhouse sector in energy models based on commercial greenhouse data in Ontario. These energy concerns can be addressed through supplemental lighting technology management and the use of distributed energy resources (DERs). This work provides significant research contribution by presenting three different studies that analyze various supplemental lighting technologies and DER systems based on real systems. These studies provide a range of scenarios at a finer geographic scope to anticipate the potential growth of electrical loads. Together, these designs and analysis provide projected impacts, modelling tools, and various mitigation strategies with supplemental lighting and DERs in the vegetable greenhouse sector.

Chapter II studies the various supplemental lighting combinations available to the Ontario pepper greenhouse sector that currently remains largely unlit. This chapter examined the crop with no lighting, HPS, and LED lighting with both a crop focused and electrical impact headset. It was determined that any addition of lighting results in a notable increase of electricity demand and consumption. However, using LED lighting provides significant operational electricity savings to the greenhouse but come at a greater capital cost. The electrical comparison of various lighting recipes was explored in a unique model that previous studies had yet to explore. Taking this further, this study projected the impact a commonly unlit sector could have on the electricity grid if supplemental lighting became was adopted. The developed models display numerous lighting recipes with electricity modelling, capital and operational cost analysis, and the overall impact to the Ontario electricity grid.

In Chapter III, the adaptation of supplemental lighting and the expansion of harvesting acres allows for increased produce yield but also increases electrical power demand. This study models the electricity demand and consumption dependent on lighting intensity, lighting types, and sector expansion. The results show that for every 1% decrease or increase in lighting intensity, there is a significant corresponding decrease or increase impact to the electricity demand and yearly consumption. Furthering this, the results showed that if most of the current sector adapted lighting the electricity demand and consumption on the grid can increase up to fourfold. Additionally, if the sector adapted lighting and increased the harvesting area by 50% the demand and consumption can inflate up to fivefold. Overall, a mass shift to lighting could have unforseen impacts on the electricity grid. Outcomes confirm that strategic lighting intensity and technology choices can be used for grid optimization and sector success to avoid unavailable grid supply.

DER electricity generation allows for greenhouses to operate without the constraints of local electricity shortages. Chapter IV illustrates the demand and electrical consumption of five vegetable greenhouse, individually and as a five-grower network. This study examined the commercial facilities based on electrical demand and consumption for unlit and lit acres, as well as commonly used lighting hours and months for lit greenhouses. This concluded that each greenhouse has unique consumption based on greenhouse structure, crop type, and lighting habits. These five greenhouses were then combined electrically to show the unique loads of a newfound network of vegetable greenhouse facilities, a combination not yet explored in research. DER designs including cogeneration and battery were developed for both the greenhouses separately and five-grower network. The results show that by creating a network, there can be significant reduction in DER capacity, capital costs, and fuel and operational costs. This study confirmed that creating greenhouse networks can allow for greenhouses to self-generate at a reasonable cost using DERs.

FUTURE RECOMMENDATIONS

The electrical data modelling presented in these studies and their application with Ontario greenhouse data provide a sample of the complexity of supplemental lighting and DERs on the sector and provide meaningful cohesive insights for both the greenhouse and electricity industry. The diverse availability of lighting technologies and application methodologies can massively impact the power consumption of the greenhouse and ultimately the demand for DERs or grid electricity. The model results focus on a general adaptation of both supplemental lighting and DERs that can be used by both agriculture and energy policy makers, electricity system operators, and utilities to guide decisions.

The results from Chapter II showcased detailed load trends and electricity savings from using LEDs over HPS lighting systems. However, it did not explore the energy increase in systems like boilers to make up for the heat that is typically emitted from HPS lights to warm the greenhouse. There is value in future research looking at the energy nexus between more efficient lighting systems and demand changes in heating systems. In addition to this, modelling the carbon emissions from the greenhouse using less electricity from the grid and increasing its fuel consumption when switching from HPS and LED could provide the sector with critical information. An analysis like this could be of interest globally and could vary depending on the generation technology used by the electricity sector. This would provide full picture insight on if HPS to LED is truly beneficial to the sector or solely of benefit to reducing demand on the electricity grid.

Chapter III applied an average lighting intensity, fixture, and methodology to estimate the demand and consumption of the Ontario vegetable greenhouse industry on the grid. While this research provided valuable insight and projections of the sector turning to lighting, this analysis can be refined to improve the accuracy of the results. First, the lighting model could be improved by specializing the lighting technique by the crop type. This could be achieved by collecting industry data such as lighting intensities and targets used in commercial greenhouses in Ontario. This would not only provide more accurate modelling on the overall demand for grid forecasting but would showcase the defining factors on the growers end that lead to high power consumption. Furthermore, investigating common lighting hours would be beneficial in modelling an hourly demand profile of the sector and could provide the information needed to plan greenhouse demand shifting. The results from this could also lead to further investment in research targeting continuous lighting and reduced lighting days for demand reduction.

The DER design shown in Chapter IV modelled the load analysis and financial case study of a five-grower network in Southwestern Ontario. Although this research investigated a unique proposition of five greenhouses in the same area building a power network and sharing a DER system, this proposition requires further investigation before implementation. To start, the installation of such a system requires grid availability and coordination. Future studies could analyze grid availability, connectivity requirements, and the controls required to utilize a system of this nature. Additionally, to confirm the feasibility, the mapping of ownership, stakeholder, and legal relationships in a DER partnership should be explored. Further limitations of this study include the financial limitations which depend on location specific electrical loads and costs. Recommendations include up to date technology pricing, detailed projections on electricity and natural gas, and costs associated with the interconnectivity of the assets to the grid. Lastly, further exploration of DERs such as photovoltaic (PV), small modular reactors (SMRs), wind, and biogas cogeneration should be considered for the greenhouse industry.

The scenarios presented in these studies provided a unique and newfound modelling technique on the electricity portion of the greenhouse industry. However, there are opportunities to further this research to gain additional insight. Overall, the electricity and DER modelling tools introduced in this thesis must be continually updated and further explored to remain relevant to the technology and methodology utilized in modern day.

ENGINEERING CONTRIBUTIONS

The engineering contributions from the studies and models presented in this thesis can be summarized by the following points:

1. A detailed current and projected hourly and monthly load curve for characteristic greenhouse operations (Chapter II)
2. A presentation of a diverse set of lighting scenarios highlighting electricity demand and consumption variation in the greenhouse industry (Chapter II)
3. An improved financial comparison model for unlit and lit acres of a pepper greenhouse in Ontario (Chapter II)
4. A baseline comparison of the impact of various greenhouse lighting intensities and lighting technology combinations on the Ontario electricity grid (Chapter III)

5. A projection of greenhouse vegetable demand and consumption on the electrical grid based on supplemental lighting adaptation and sector expansion (Chapter III)
6. A grower network analysis of representative varying load profiles of unlit and lit vegetable greenhouses in Southwestern Ontario (Chapter IV)
7. A model design of new onsite DER assets for characteristic greenhouse operations and five-grower network (Chapter IV)
8. The development of detailed 25-year CAPEX and OPEX financial model of a cogeneration and battery system considering project and location-specific factors such as: capital expenses, electricity and natural gas cost projections, agriculture rebates, technology costs, grid savings (Chapter IV)
9. A report of baseline electricity costs per kWh for centralized and decentralized energy supply architecture (Chapter IV)

The previous studies addressing supplemental lighting focus solely on the greenhouse sector at a research level, with commercial data not being readily available. The models developed in this thesis provide load analysis using scenario impacts from the sectors innovation and expansion projections backed by industry data that can be used for electricity planning. Furthermore, the development of a five-grower network DER cogeneration system provides tangible designs and opportunity ideas that can be used in the sector today. In conjunction, the models provide a toolset for planning the future impact of the greenhouse sector on the energy industry.

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