Adaptive Lighting Control Technology for Greenhouses

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Adaptive Lighting Control Technology for Greenhouses

Final Report

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Abstract

Adaptive lighting control is an emerging strategy to reduce electricity use of greenhouse supplemental lighting systems. This is accomplished using a lighting controller connected to a photosynthetic active radiation sensor that together constantly measure and integrate the amount of sunlight received by greenhouse crops. Supplemental lighting energy use is minimized by optimizing the use of sunlight while ensuring that the crop daily light integral is consistently met. The objective of the present study was to investigate the energy savings potential of an adaptive lighting controller system installed in a greenhouse located in North Tonawanda, New York. A control plot and test plot of equal size (2,100 ft^2) were set up in adjacent deep water culture ponds producing butterhead lettuce, each using supplemental LED lighting to achieve a daily light integral of 18 $mol/m^2/d$. The test plot utilized an adaptive lighting control system developed by Candidus, Inc., and the control plot utilized the greenhouse's existing lighting control strategy (a combination of photoperiod and lighting threshold). Results of the trial demonstrated an estimated annual supplemental lighting system energy savings potential of approximately 26%, equating to 8.1 kWh/ft^2 for a greenhouse matching the characteristics of trial greenhouse site and crop. Crop performance was also measured throughout the trial, and no significant differences in crop performance were observed between the two plots. Based on the findings of this trail, adaptive lighting control has potential to significantly reduce greenhouse supplemental lighting energy use and energy costs, with an estimated simple payback period ranging from one to four years. The technical potential of electricity savings within New York State associated with greenhouse adaptive lighting control is estimated to be between 11.65 and 81.55 gigawatt-hours.

Keywords

Horticultural lighting, controlled environment agriculture, energy efficiency, lighting controls

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Acronyms and Abbreviations

CEA	Controlled environment agriculture
CT	Current transformer
DLI	Daily light integral
DWC	Deep water culture
GWh	Gigawatt-hour
HID	High intensity discharge
HPS	High pressure sodium
LED	Light emitting diode
M&V	Measurement and verification
NYSERDA	New York State Energy Research and Development Authority
kW	Kilowatt
kWh	Kilowatt-hour
PAR	Photosynthetic active radiation
PPF	Photosynthetic photon flux
PPFD	Photosynthetic photon flux density
ROI	Return on investment

1 Introduction

Controlled environment agriculture (CEA) is increasingly viewed as a critical strategy for producing food in a localized and resource-efficient manner in New York State (NYSERDA, 2019; Cornell, 2019). Greenhouse crop production is the most prevalent form of CEA in the State and is expected to increase in magnitude for the foreseeable future. Energy is the second-highest operating cost for greenhouses and the electricity used to power greenhouse supplemental lighting can amount to 30% of operating costs alone (Watson et al., 2018). Energy efficient supplemental greenhouse lighting is an increasingly important strategy to maximize greenhouse productivity and profitability. While the transition from high-intensity discharge (HID) lighting to light-emitting diode (LED) technology is underway, an emerging technology known as adaptive lighting control (also known as dynamic lighting control) can further reduce electricity costs while maintaining or improving crop yields, particularly for growers utilizing basic lighting control systems such as timeclocks.

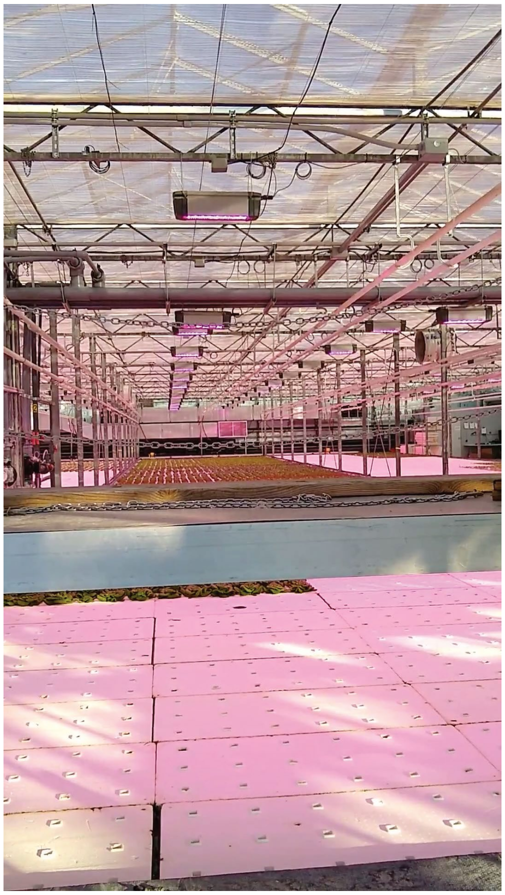
Adaptive lighting technology has been commercially available for several years in the United States but has had minimal market penetration among commercial greenhouse growers. Adaptive lighting controllers reduce the use of greenhouse lighting system energy by dimming supplemental lighting in response to available sunlight, thereby reducing excessive illumination. The technology consists of photosynthetic active radiation (PAR) light sensors and central controllers, each capable of supporting hundreds of light fixtures in multiple zones. The controller is programmed with a crop-specific daily light integral (DLI) value which informs the dimming algorithm, resulting in the crop receiving a more consistent DLI throughout the growth cycle. DLI is the measurement of accumulated photosynthetic light throughout the day, which varies with cloud cover and other environmental factors. Each crop has a minimum DLI value for optimal productivity in each stage of its life cycle, after which additional lighting has diminishing returns on yield. Monitoring photosynthetic light levels and adjusting the output of the supplemental lighting system to achieve optimal crop DLI is a key innovation of adaptive lighting system. It is designed to not only provide the crop with a consistent and appropriate amount of light energy each day, but also minimize the amount of electricity consumed.

This report details the results of a seven-month trial funded by NYSERDA to evaluate an adaptive lighting controller system manufactured by Candidus, Inc. The trial took place at Wheatfield Gardens, a commercial greenhouse operation located in North Tonawanda, NY. The study was led by EnSave, Inc. and included on-site energy metering support from C.J. Brown Energy & Engineering. The overarching objective of the study was to evaluate the energy savings potential of the adaptive lighting controller and the impact on crops grown.

2 Study Design and Setup

The study design involved setting up test and control plots of equal size, each of which produced butterhead lettuce grown in floating rafts in a deep-water culture hydroponic pond (Figure 1).

Figure 1. LED Lighting Fixtures over Deep Water Culture Pond Trial Location



Energy metering hardware was installed by C.J Brown Energy & Engineering to independently record voltage, amperage, and kilowatt-hour usage for the lighting systems serving each plot. Crop performance was evaluated through site visits that involved taking photos of each plot at different stages of crop maturity. Measurements of lettuce head weights and evaluation of physical characteristics took place at the end of the crop cycle. The following sections provide a detailed description of the energy and crop evaluation portions of the study design.

After an initial visit to Wheatfield Gardens to examine the test location, it was determined that the existing Senmatic lighting controller was more sophisticated than standard greenhouse industry practice in that it used a PAR meter to turn off the LED lights when a pre-programmed instantaneous light threshold is reached (see section 2.1). For this reason, it was mutually decided by the project team that the energy performance of the adaptive lighting controller would be evaluated using two baselines. The first baseline would use metered energy data collected by C.J. Brown in both the test and control plots. The second baseline would be a computer simulated model replicating a simple on/off timeclock lighting controller as the baseline condition, which is thought to be a closer approximation of industry standard practice (although this is not precisely known due to a lack of available greenhouse baseline information). The model would assume identical installed lighting capacity (kilowatt) and target DLI as the test plot. To ensure that the savings in the modeled baseline would be defensible, the energy usage of the test plot would be based on metered data in both scenarios.

2.1 Energy Metering Protocol and Hardware Setup

The energy measurement and verification (M&V) portion of the study utilized two 2,100 square foot plots of butterhead lettuce grown in floating rafts in deep water culture hydroponic ponds. The control plot used the facility's existing Senmatic LED lighting controller and existing settings, which turned on the lights at 3:30 a.m. and turned them off for the day once the target DLI of 18 moles per meter squared per day (mol/m^2/d) was delivered to the plants. The Senmatic lighting controller made use of a PAR meter mounted inside of the greenhouse that provided instantaneous photosynthetic photon flux density (PPFD) measurements to the Senmatic controller which was programmed shut off fixtures temporarily when an instantaneous PPFD reading of 500 micromoles per square meter per second (µmol/m^2/s) was reached (a combination of sunlight and supplemental light).

Each plot was illuminated by 26 Osram HL300 Grow LED fixtures. Two fixtures were located over a walkway and were not included in the metering, leaving 26 fixtures per plot. The fixtures in each plot were powered through four circuit breakers, each of which served between six and seven fixtures. A Dent Elite Pro power meter with data logging capabilities and four current transformers (CTs) was used to measure voltage and current at the four circuit breakers, kilowatt (kW) and kilowatt-hour (kWh) values associated with 13 of the 26 fixtures in the test plot, and 14 of the 26 fixtures in the control plot. Instantaneous power and power usage (kW and kWh) were calculated by the data logger for those circuits. Measurement of amperage only was conducted for the remaining four circuits (two in the test plot and two in the control plot) to ensure the circuits were controlled in the same manner as those circuits measured as the fixtures with kW and kWh data.

The circuits were measured using a four-channel amp meter (also with data logging capabilities) and four CT's.

The kWh meter included three voltage measurement channels and four current measurement channels.

- One voltage channel was used to measure the line voltage level of the control plot circuit.
- One voltage channel was used to measure the line voltage level in the test plot circuit.
- One voltage channel was not used.
- Two current measurement channels were used to measure amperage at the two circuit breakers to the test plot fixtures.
- Two measurement current channels were used to measure amperage at the two circuit breakers that control plot fixtures.
- The voltage and current measurements were used by the meter to calculate kW and kWh.

Current transformers were installed in the junction box above the breaker panel, with leads exiting the box through an unused conduit opening on the bottom of the box. The kWh meter was attached to the outside of the junction box by magnets in its base. Voltage was measured by hard-wired connections inside the circuit breaker panel. Voltage leads were attached to the grounding bar and to one of the circuit breakers to be measured. Voltage leads exited the panel at the top using a conduit knock-out and were secured to the conduit leading to the junction box and the kWh meter.

The meters were installed inside the circuit breaker panel and began logging data around 8:30 a.m. on December 12, 2019. The meters were programmed to sample continuously and record average values at intervals of two minutes. Data was downloaded manually by C.J. Brown Energy & Engineering during four site visits conducted throughout the seven-month trial period.

2.1.1 Adaptive Lighting Controller Setup

Installation of the Candidus adaptive lighting controller was completed between December 12, 2019 and December 13, 2019. Figure 2 shows the adaptive lighting controller box, which contains the processor and analog module. Figure 3 shows a controller installation at Wheatfield Gardens. The analog module collects sunlight intensity from a PAR (photosynthetic active radiation) sensor that was installed above the LED lighting fixtures above the test plot. The adaptive lighting controller was configured to bypass the Senmatic controller for 26 fixtures illuminating the test plot.

At the request of Wheatfield Gardens, the adaptive lighting controller was initially programmed to prioritize achieving the target DLI instead of energy savings. On darker days when sunlight is not sufficient to achieve the target DLI, the Candidus controller maximized supplemental lighting to reach the target DLI. This provided a more consistent level of lighting in the test plot than in the control plot, which was expected to achieve more predictable production yields and expedite crop maturation.

Figure 2. Adaptive Lighting Controller System

Figure 3. Adaptive Lighting Controller During Installation

2.2 Crop Performance Evaluation Protocol

Throughout the trial period, crop data was collected to compare performance of the test and control plots. Four key crop performance metrics were evaluated: (1) crop cycle length, (2) lettuce head volume, (3) weight per head of lettuce, and (4) visual characteristics. Crop data collection was conducted by a combination of staff at Wheatfield Gardens and a subcontracted local horticultural undergraduate student. All photographs taken of the test and control plot crops adhered to the same methodology to ensure no bias. Table 1 provides an overview of the metrics used to evaluate crop performance, and the days within the crop cycle scheduled for data collection.

Table 1. Overview of Crop Data Collection Parameters

Crop Metric	Metric Reporting Deliverables	Day(s) of Growth Cycle that Data is Collected
Volume	High resolution photographs of both test and control plots, including photos of a random sample of five mature heads per plot in clam shell containers taken in a photo box.	Day 14, Day 28, Harvest
Weight	Measurement of grams per mature head using a digital scale. Measurements will be taken for a random sample of five mature heads per plot.	Harvest
Crop cycle	Documentation of crop start date and harvest date to calculate total days of growth cycle.	Day 1, Harvest
Visual Evaluation	High resolution top-down photographs of both test and control plots, and closeup photos of a random sample of mature heads after harvest.	Day 14, Day 28, Harvest

3 Results of Energy Metering

3.1 Metered Data Findings and Observations

Metered energy data was provided by C.J. Brown Energy to EnSave on four occasions over the energy metering period: March 25, 2020, May 22, 2020, July 14, 2020, and August 28, 2020. In reviewing the first batch of metered energy data provided by CJ Brown on March 25, 2020, it was discovered that the control plot consumed approximately 47% less energy (kWh) than the test plot. EnSave and Candidus investigated and discussed this issue extensively and identified the following possible causes:

1. The control plot lighting controller is under-driving the lighting fixtures such that they only reach a maximum output of approximately 76–80% of the Candidus-controlled fixtures. This was determined based on metered data, which shows that the maximum kWh consumption per fixture is 24% lower in the control group versus the test group during Cycle #1. Since both the test and control plots are using identical LED fixtures, the energy consumption should be identical when the fixtures in either group are at 100% intensity.
2. There is a minor increase in energy use by the Candidus-controlled lights due to the in-fixture fans being run continuously.
3. During times of low available sunlight, the Candidus-controlled lights were operating constantly at maximum output because, per the greenhouse growers' preference, the controller prioritized reaching the target DLI (18 mol/m2/day). Conversely, the Senmatic-controlled lights are programmed to shut off intermittently when a maximum lighting threshold (combined sunlight and supplemental light) is reached, which overrides the DLI objective. Thus, the test plot fixtures provided more light than the control plot fixtures, although no benefits in crop performance were observed.

Although these were all important variables, it was ultimately determined that the existing PAR light sensor connected to the Senmatic controller in the control plot was faulty and was registering light levels roughly double that of the readings from the PAR meter in the test plot. The readings of each light sensor were compared to the readout of a correctly calibrated light sensor that was brought to Wheatfield Gardens on August 27, 2020. The miscalibration of the existing light sensor at Wheatfield Gardens resulted in the control plot lights turning on less frequently than the test plot lights. The difference in energy use between the test and control plots was magnified during times when there was sunlight entering the greenhouse and as the days became longer, and undoubtedly resulted in the control plot falling significantly short of the target DLI.

As a result of the incorrectly calibrated PAR sensor connected to the control plot, the metered data did not provide a reliable basis for directly comparing energy usage of the test plot and control plot. However, the energy metering served the important function of validating the modeled energy usage of the test plot, which provided confidence in the accuracy of the modeled baseline energy usage reported by the Candidus controller (see section 3.3 for more details). Metered data was also used to identify anomalies in controller performance, described further in section 4.3.

3.2 Modification to Adaptive Lighting Controller Settings

Based on the initial analysis of metered energy data from Cycle #1 and subsequent discussions between Wheatfield Gardens, EnSave, and Candidus, the following changes to the adaptive lighting controller settings were identified to normalize the baseline testing conditions of the test and control plots and attempt to increase energy savings in the test plot. To achieve these objectives, Candidus suggested the following changes to their controller protocol:

1. Normalize the maximum lighting output capacity of the light fixtures by reducing the maximum power output from Candidus-controlled fixtures to 80% intensity to match the maximum power consumption of the Senmatic-controlled fixtures.
2. Reduce the DLI target since the target DLI was not able to be achieved in either the control or test plots. The Candidus system was originally set to prioritize DLI, which resulted in the test group light fixtures continuously operating at maximum intensity. This is an indication that the lighting capacity is not sufficient to reach the desire DLI at certain times of year when there is less sunlight (such as during Cycle #1), even with maximum supplemental lighting. Conversely, the control group fixtures shut off periodically based on a light threshold of 500 µmol/m2/s (combined instantaneous sunlight and supplemental light).
3. Implement a threshold shutoff control in addition to the DLI control. This would allow the Candidus-controlled lights to turn off during times of high illuminance (full sun) to match the Senmatic-controlled fixtures, rather than remaining on to prioritize reaching the target DLI.
4. Shift photoperiod from 3 a.m.–7 p.m. to 4 a.m.–8 a.m., which would be implemented in both the control and test groups to allow more efficient utilization of sunlight with the seasonal change. When necessary supplemental lighting is provided later in the day instead of earlier in the day, it allows the adaptive lighting controller to take full advantage of the natural sunlight and avoids potential energy waste provided before sunrise. With longer and brighter days there are increased instances in which supplemental lighting is not needed.
5. Reduce the maximum power output of the test plot fixtures to 50% between 4 a.m. and 9 a.m.. This recommendation was made based on Wheatfield Gardens' observation that the lettuce heads exceeded the saleable size in both groups and with the additional available sunlight during Cycle #2, no adverse impacts on crops are expected. This setting would help prevent "DLI overshoot," which occurs on days when there is sufficient sunlight to reach the target DLI before sundown.

Each of these proposed changes was reviewed by and discussed with Wheatfield Gardens. To maintain integrity of the testing methodology, it was decided that only changes #1, #3, and #4, and #5 would be implemented. All these changes, except for #5, primarily served to normalize the baseline controller protocol of the test and control groups based on lessons learned during Cycle #1. The justification for implementing change #5 was to exploit an advantage of the Candidus controller based on the host site's recommendation and prevent overshooting the DLI target on sunny days.

3.3 Modeled Baseline Findings and Observations

Potential energy savings of the adaptive lighting controller was calculated by comparing the metered energy usage of the test plot with modeled energy usage of the control plot, reflecting a baseline condition where lighting fixtures are controlled with a timeclock. A timeclock-based lighting control method was selected as the baseline condition because it is assumed to be industry standard practice in New York State; however, there is no available industry data to confirm this assumption. Quantifying energy savings by using a modeled baseline approach was necessary due to the incorrect calibration of the existing on-site PAR sensor, which resulted in artificially low-control plot energy usage (see section 3.1). Potential electricity savings is reflected in each of the monthly reports provided to Wheatfield Gardens (see appendix B), which ranges from 4.6% to 52.2% versus a timeclock-controlled baseline. Energy usage shown in the Candidus monthly reports was verified by EnSave and C.J. Brown to conform precisely with the metered energy use in the test group.

Table 2 provides an overview of modeled energy savings achieved by the adaptive lighting controller in the test plot, which covered 2,100 square feet and had 15.6 kW of installed lighting capacity (26 fixtures, 600W each). Since the submeter ing period did not extend past the summer, energy and cost savings values in Table 2 for the period of September to December (highlighted blue) are based on the metered data collected from January through April.

Table 2. Monthly Adaptive Lighting Controller Energy Savings Based on Modeled Baseline

	January	February	March	April	May	September	October	November	December
Energy Savings (%) a	4.40%	14.80%	26.60%	44.60%	52.20%	44.60%	26.60%	14.80%	4.40%
kWh Savings	342	1,074	2,061	3,166	3,784	3,166	2,061	1,074	342
Energy Cost Savings b	$34	$107	$206	$317	$378	$317	$206	$107	$34
Cumulative Cost Savings	$698	$806	$1,012	$1,328	$1,707	$317	$523	$630	$664
Cumulative kWh Savings	6,985	8,058	10,119	13,285	17,068	3,166	5,226	6,300	6,642

[a] Energy savings in June, July, and August was excluded due to anomalies observed in the metered energy use data in these months (see section 3.4.1).

[b] Energy cost savings is based on a cost of $0.10/kWh.

Energy savings in darker months is lower due to less available sunlight, meaning that there is less opportunity for the adaptive lighting controller to dim the supplemental lights during the lights-on period. This was particularly true at Wheatfield Gardens, where the supplemental lighting system operating at full intensity was insufficient to achieve the target DLI (18 mol/m^2/day), resulting in the lighting fixtures in both the control and test plots operating at full power almost continuously in January.

As the day length increases between the winter and summer solstices, the potential for energy savings increases proportionally. This effect can be seen in Table 2, where savings versus the modeled baseline increases from 4.4% in January to 52.2% in May. Average annual energy savings was approximately 26%, with a cumulative cost savings of $1,707 (based on $0.10/kWh rate).

3.4 Unexplained Issues and Confounding Factors

There were several unexplained issues and confounding factors encountered over the energy metering and data monitoring period. Each of these issues is summarized below.

3.4.1 Abnormally Low Energy Use in Control Plot

As discussed in section 3.1, EnSave observed an unexpected issue after the first metered data was received on March 25, 2020, which showed that the control plot was using significantly less electricity than the test plot. Several theories were developed to account for this difference, including the possibility that the Senmatic lighting controller was under-driving the fixtures in the control plot.

Several modifications to the adaptive lighting controller (described in section 2.1) were devised to improve the energy performance of the adaptive lighting controller without compromising the underlying study design. These changes were implemented on April 6, 2020, but ultimately only led to increased savings when compared to the modeled baseline. The magnitude of energy usage of the test plot steadily increased in comparison to the control plot as the day length increased, amounting to an average of approximately 69% greater electricity usage between April 7, 2020 and August 21, 2020 reflected in the metered energy data.

3.4.2 Similar Crop Performance Despite Differences in Achieved DLI

Following the discovery of the light sensor calibration issue, and the realization that the control plot was receiving significantly less light, a subsequent question arose: Why is the crop performance in the control plot similar to the test plot if the control plot is receiving significantly less light? Although the weight of the crops in the test plot was higher than in the control plot in the final crop cycle, the difference in weight and appearance was not significant.

One possible explanation for the similar crop performance under different lighting DLIs is that the reduced lighting in the control period was compensated for by carbon dioxide supplementation taking place in the greenhouse. In other words, any negative crop growth impacts resulting from suboptimal DLI achieved in the control plot may have been counteracted by the supplemented carbon dioxide, whereas the maximum growth potential was reached in the test plot using a different metabolic strategy (utilizing more light and less carbon dioxide).

3.4.3 Lighting Controller Operation Interruptions

Two notable operational anomalies were observed over the metering period. The first occurred on June 15, 2020 when there was a four-hour period during which the voltage readings for both the test and control plots registered zero, after which the metered data for the test plot started reading approximately 11.5 volts continuously until June 27, 2020. It is unclear what caused this interruption, but it may have been related to a power outage.

The second interruption occurred on July 27, 2020, when the metered amperage for the test plot registered zero for the remainder of the metering period. This anomaly was discovered on August 28, 2020 when data was retrieved by C.J. Brown Energy. It is unclear what caused this interruption in the metered data. Due to the interruptions in metered data and operation of the adaptive lighting controller observed in June and July (extending into August), metered data from these months was excluded from analysis.

3.5 Technology Lessons Learned and Recommendations

This trial provided an important opportunity to test adaptive lighting control in a commercial greenhouse setting. The number of variables influencing plant growth and supplemental lighting system energy usage introduced unexpected difficulties, but also provided important lessons for future trials of horticultural lighting energy use in greenhouse environments. Key lessons regarding energy metering and lighting system setup are summarized below.

1. Live data monitoring with a web-based data acquisition system would provide a major advantage in detecting and resolving issues and anomalies quickly and minimizing impact to the project timeline and budget. It would also allow for data analysis to begin sooner and allow a more dynamic evaluation of the technology performance. Adjustments to lighting system operating parameters could be observed immediately and readjusted as needed. Additionally, a metering system that could send alerts for power outages and other critical events would be useful.
2. Verifying that all reference equipment is reporting accurately is a critical phase of the test commissioning process. This includes all sensors, meters, and other data collection devices used in the project. Equipment calibration compliance with manufacturer specifications, National Institute of Standards and Technology (NIST) guidelines, or other certification bodies should be completed where possible. Configuration settings and data from technology that is under evaluation should be verified by the manufacturer. All systems checks should be documented. In this trial, verifying proper calibration of both PAR meters (quantum sensors) at the start of the study would have identified an important confounding issue.

3. Equipment operational characteristics, settings, and reporting metrics between two systems that are being compared should be verified before the start of the test. This may be difficult to get exactly right if the systems are designed or specified differently, but an initial evaluation should be completed, and the comparison documented. For example, ensuring that the maximum light output of both the test and control plots is equal can identify under-driving (dimming) or over-driving of fixtures by lighting system controllers.
4. An initial evaluation of lighting system capacity should be done before setting the desired DLI for the greenhouse. Assuming a rainy day with maximum cloud cover and short daylight hours, the lighting configuration needs to be able to provide enough photosynthetic energy to achieve the desired DLI. If not, additional lighting capacity (or reconfiguration of fixtures) would need to be implemented before the adaptive lighting system can perform optimally. Alternatively, a maximum daily runtime could be implemented if achieving maximum DLI every day is not critical.
5. A pre-programed time window was used to control when the adaptive lighting control is active. In the trial, this window was adjusted due to seasonal changes in day length. It may be advantageous to utilize weather forecast data to determine when the system should be activated to maximize sunlight utilization and/or avoid exceeding the target DLI.

4 Results of Crop Performance Monitoring

The crop monitoring period spanned four complete crop cycles over a period of 220 days, beginning on January 14, 2020 and ending on August 21, 2020. Several factors complicated data collection following the first crop cycle, including visiting restrictions due to COVID-19; an insect-related disturbance during the final week of Crop #2; and miscommunications between crop management staff at the project site and the crop data collector that resulted in an inability of the data collector to access the crop location. Despite these setbacks, partial crop performance data was collected for each of the crop cycles, and harvested crop measurements were collected for the final crop cycle. To address gaps in the crop measurement data and ensure that the adaptive lighting control system was not adversely impacting crop performance, correspondences were made with crop management staff at Wheatfield Gardens to confirm that lettuce heads in the test plot were performing as well or better than the control plot during the monitoring period.

Table 3 provides a summary of the site visits scheduled and completed; canceled site visits are highlighted yellow.

Table 3. Summary of Crop Data Collection Site Visits

Crop Cycle	Date Lettuce Placed into Plots	Site Visit #1	Site Visit #2	Site Visit #3 (Harvest)	Crop Harvested?	Differences Observed in Crop Performance?
1	1/14/20	1/15/20	2/17/20	3/6/20	Yes	No
2	3/20/20	3/30/20	(Canceled)*	(5/23/20)	No	No
3	5/23/20	5/23/20	(6/27/20)	(7/11/20)	No	No
4	7/11/20	7/11/20	(8/8/20)	8/21/20	Yes	No

* Canceled due adherence to recommended COVID-19 protocols.

The following sections provide a detailed account of each site visit. Despite needing to cancel four site visits, partial data was able to be collected with the assistance of Wheatfield Gardens staff, which provided reasonable evidence that the test and control crops performed similarly.

4.1 Crop Cycle #1

The first butterhead lettuce crop (Cycle #1) was started on January 4, 2020 and was placed into the hydroponic test and control plot areas at the Wheatfield Gardens on January 14, 2020. The crop data collector visited Wheatfield Gardens on January 15, 2020 and took pictures of the planted hydroponic lettuce rafts (see appendix A). The second site visit took place on February 17, 2020, during which photos of the test and control plots were taken to compare growth progress. The final site visit for Cycle #1 occurred on March 6, 2020, during which a random sample of 12 lettuce heads were selected for harvest (six from each plot), weighed on a digital scale, and photographed in a portable photo studio box. Appendix A contains photos taken of the first crop cycle by the crop data collector.

Table 6 provides a summary of the lettuce head weights in grams. Weights were taken for six heads of lettuce randomly selected by the crop data collector for each plot and were measured using a digital scale. The mean weight for the test plot heads was 241g, and the mean weight for the control plot heads was 274g, implying that the average weight of control plot lettuce heads was approximately 14% higher than the test plot heads. However, given the small sample size, the p-value for this comparison is approximately 0.24, meaning that the results are not statistically significant (which would require a p-value < 0.05). More importantly, the lettuce heads from the test plot were deemed adequate for sale by Wheatfield Gardens since they fit properly into the plastic clam shell and weigh over 200 grams (with the exception of one head). Table 4 provides the weight measurements for Cycle #1.

Table 4. Harvested Lettuce Head Weights (Crop Cycle #1)

Lettuce Head #	Test Plot Weight (grams)	Control Plot Weight (grams)
1	243	249
2	179	314
3	248	328
4	283	201
5	262	325
6	228	228
Mean	**241**	**274**

4.2 Crop Cycle #2

The second crop cycle (Cycle #2) was started on March 20, 2020 and was placed into the test and control plots on March 30, 2020. The two-week delay between the first and second crop cycles was due to a combination of ongoing evaluation of Cycle #1 results, and complications relating to adherence to COVID-19 protocols. The second site visit for Cycle #2 was cancelled to reduce risk to the crop data collector and host site staff amid the COVID-19 shutdown.

4.3 Crop Cycle #3

Crop #3 was placed into the test and control plots on May 23, 2020. The mid-growth cycle site visit for Crop #3 was scheduled for June 27, 2020 but was not completed because the crop data collector was unable to reach the crop manager at Wheatfield Gardens. The crop manager later provided photos of fully mature lettuce heads in the test and control plots on July 6, 2020. Based on an examination of the test and control plot photos, there is no discernable difference in crop quality; this was confirmed by two Wheatfield Gardens staff overseeing the trial crops.

Following receipt of the crop photos on July 6, 2020, a site visit was scheduled for July 11, 2020 to take photos and weights of the test and control plots. However, prior to the site visit it was learned that Crop #3 had been discarded due to a miscommunication between crop management staff at Wheatfield Gardens. As a result, the visit on July 11, 2020 was used to document the start of Crop #4.

4.4 Crop Cycle #4

The fourth crop of butterhead lettuce was placed into the test and control plots on July 11, 2020. Wheatfield Gardens' crop management staff provided a photo of the test crop on August 8, 2020 (see appendix A) and reported that the crop would be ready for harvest on August 14, 2020, which was earlier than expected due to a higher amount of sunlight during the crop cycle. No discernable visual differences were reported between the test and control plots at this time.

A site visit was scheduled for August 17, 2020 to take photos and weights of harvested crops but was canceled on August 16, 2020 due to the data collector falling ill. Wheatfield Gardens was able to enlist an employee to take photos and weight measurements on August 21, 2020. A sample of six lettuce heads from the test and control plots each were originally to be measured, but two lettuce heads from the control crop had been discarded prior to August 21, 2020 due to concerns over root rot. As with all previous crop cycles, no substantive differences were documented between the test and control crops during this cycle.

Table 5 provides the results of measured weights for Crop #4.

Table 5. Harvested Lettuce Head Weights (Crop Cycle #4)

Lettuce Head #	Test Plot (Pond #2) Weight (Grams)	Control Plot (Pond #3) Weight (Grams)
1	538	406
2	446	280
3	480	510
4	370	480
5	388	N/A*
6	384	N/A*
Mean	**434**	**419**

* Removed from the control plot due to concerns over root rot.

4.5 Crop Performance Monitoring Lessons Learned and Recommendations

Although the team was unable to collect a complete set of crop performance data as originally planned, including weights and photos of each of the four crop cycles, enough evidence was obtained to reasonably conclude that there are no adverse impacts from the adaptive lighting system on butterhead lettuce crop performance at the host site. The minor differences observed (e.g., in lettuce head weights) were not significant and were not consistent between crop cycles, which was corroborated by the two complete sets of crop harvest data, and visual inspections by crop management staff at Wheatfield Gardens. Furthermore, the changes implemented to the controller system in the test plot appear to have improved energy savings without any difference in crop performance.

Several key lessons were learned during the crop monitoring phase of this project which can help to better inform future study designs. Foremost, the challenges of working with a highly dynamic greenhouse environment with multiple points of contact and movable crops with multiple stages of growth became increasingly apparent. Strategies to minimize points of contact, and to gather visual data remotely (e.g., through WiFi cameras) should be explored in future greenhouse projects involving crop monitoring.

Additionally, having a full understanding of the crop cycle process and points of contact during each phase is critical to avoid miscommunications. In the case of this project, EnSave has worked with four separate points of contact, each of which handle different aspects of crop production. Assigning one point of contact for the crop data collector to work with will minimize opportunities for miscommunication in similar projects.

5 Environmental and Economic Benefits

Table 3 provides an overview of estimated simple payback period and return on investment (ROI) for the adaptive lighting controller when compared to the timer-based lighting system data (second baseline) that is believed to be most representative of typical producer greenhouses. Electricity costs ranging from \$0.04 to \$0.14 per kWh were evaluated. The actual cost per kWh at Wheatfield Gardens is difficult to determine due to their use of a combined heat and power system, as well as arrangements Wheatfield Gardens has with its electric utility company that provide discounted electricity. Calculations of simple payback and ROI in Table 6 are based on an installed cost of \$5,000 and the test plot area of 2,100 ft^2, equating to \$2.38 per square foot.

Table 6. Adaptive Lighting Controller Simple Payback Period and ROI Estimates for a 2,100 ft^2 Greenhouse

Electricity cost per kWh	\$0.04	\$0.05	\$0.06	\$0.07	\$0.08	\$0.09	\$0.10	\$0.11	\$0.12	\$0.13	\$0.14
Simple payback (years)	4.10	3.28	2.73	2.34	2.05	1.82	1.64	1.49	1.37	1.26	1.17
ROI	24%	31%	37%	43%	49%	55%	61%	67%	73%	79%	85%

Each adaptive lighting controller can support up to 200 HID or LED fixtures, covering a canopy area of approximately half an acre for most crops. The installed cost of the adaptive lighting controller system decreases significantly for larger installations. The minimum installed cost of a Candidus adaptive lighting controller system is currently \$5,000, and the installed cost for a one-acre operation would typically be \$7,500, equating to installed cost of \$0.17/ft^2. Table 7 provides extrapolated savings for a one-acre installation with the same lighting power density (W/ft^2) and target DLI used by Wheatfield Gardens in its butterhead lettuce production area.

Table 7. Adaptive Lighting Controller Simple Payback Period and ROI Estimates, 1-Acre Area

Electricity Cost per kWh	\$0.04	\$0.05	\$0.06	\$0.07	\$0.08	\$0.09	\$0.10	\$0.11	\$0.12	\$0.13	\$0.14
Simple Payback (Years)	0.53	0.43	0.35	0.30	0.27	0.24	0.21	0.19	0.18	0.16	0.15
ROI	188%	235%	282%	329%	376%	423%	470%	517%	564%	611%	658%

Results of the modeled energy savings indicate an estimated annual energy savings of approximately 8.1 kWh/ft^2 for a greenhouse matching the characteristics of Wheatfield Gardens, assuming a basic on/off lighting control strategy as the baseline.

Note that the simple payback and ROI for the adaptive lighting controller vary depending on several factors, including:

- Number and wattage of fixtures (load) connected to the controller.
- Cost of electricity at greenhouse.
- Target crop DLI and photoperiod.
- Average annual sunlight available at the greenhouse.
- Existing (baseline) lighting technology and control strategy at greenhouse.

5.1 Estimated Statewide Impacts

There are an estimated 1,908 greenhouse operations in the State, 237 of which are over 20,000 square feet in size (NYSOITS, 2020). The total amount of land covered by greenhouses throughout the State is estimated to be over 648 acres (USDA, 2017). While the percentage of the area in each greenhouse using supplemental lighting is unknown, it is estimated to fall between 10% and 20% and mainly consist of larger operations that account for the majority of New York State’s greenhouse crop output.

We estimate that adaptive lighting control currently has a maximum annual electric savings potential range of 11.65 gigawatt-hours (GWh) to 81.55 GWh. Achievable statewide savings of the technology likely ranges from 0.5% to 2.5% of the maximum potential and will depend largely on willingness of growers to adopt technology, which is influenced by available incentives, payback period, and non-energy benefits such as data insights and greater control over the lighting system. The range in potential savings is attributable to variable weather conditions, wide ranging crop, DLI targets, and unknown baseline of installed lighting system characteristics (e.g., lighting Watts per square foot). Savings potential for adaptive lighting controllers is expected to increase steadily as more greenhouses are built and the use of supplemental lighting adoption increases. The recent legalization of recreational cannabis may also increase statewide savings potential for this technology.

Table 8 provides an analysis of a low and high estimate of energy and cost savings potential of the adaptive lighting controller technology.

Table 8. Estimated Statewide Energy Impacts of Adaptive Lighting Controller Adoption

Metric	Low Estimate	High Estimate	Notes
Estimated total New York State greenhouse area with supplemental lighting (square feet).	2,824,217	5,648,433	Low and high estimates represent 10% and 20% of total New York State greenhouse area (USDA, 2017), respectively.
Average lighting power density (LPD) (Watts/square foot).	8.25	13.75	Estimate based on DOE (2020) study, where low and high estimates are 25% lower and higher than the average greenhouse lighting power density of 11 Watts per square foot.
Average daily hours of lighting system operation.	5.48	8.22	Annual hours of operation vary depending on crop DLI, weather, and other factors. Low estimate is 2,000 hours per year, and high estimate is 3,000 hours per year.
Estimated annual New York State greenhouse supplemental lighting electricity consumption (kWh).	46,599,572	232,997,861	
Estimated annual greenhouse supplemental lighting kWh consumption per square foot.	16.5	41.3	Lighting kWh usage per square foot varies significantly depending on lighting technology type (e.g., HPS vs. LED) and crop DLI.
Estimated annual energy savings from adaptive lighting control.	25%	35%	Savings range is based on the results of this study, as well as previous research by Van Iersel & Gianino (2017).
Estimated annual kWh savings potential.	11,649,893	81,549,251	
Average cost per kWh paid by greenhouses.	$0.07	$0.14	
Annual energy cost savings potential from adaptive lighting control.	$815,493	$11,416,895	

6 Conclusions and Opportunities for Further Improvement

Adaptive lighting control is a promising underutilized technology that can significantly reduce the energy consumption of greenhouse supplemental lighting systems. While the trial presented in this paper encountered numerous challenges, it was effective in demonstrating compelling savings potential and ROI of the technology. It also exposed opportunities for improvement relating to the implementation and effectiveness of the technology, and best practices for conducting similar horticultural lighting controller studies.

Several variables could not be fully evaluated in this trial, including the impact of climate zone, greenhouse construction type, and crop type on the energy saving performance of adaptive lighting controllers. Further trials of this technology should address these variables while seeking to minimize potential confounding crop performance factors such as differences in temperature, humidity, and carbon dioxide concentration in the control and test plots. Subsequent studies are merited to quantify the potential energy and cost savings and return on investment for discrete groups in a broader and representative set of greenhouse operations.

Key variables that affect energy savings and return on investment of greenhouse adaptive lighting control include the combined wattage of fixtures connected to the controller, cost of electricity, target crop DLI, photoperiod, annual solar irradiance, the baseline lighting system technology type (i.e., LED vs. HID), and the baseline lighting control strategy. The simple payback period decreases significantly when the maximum number of lights are connected to the controller; in general, the payback will be shorter for larger greenhouses, particularly those growing crops with higher target DLIs. Savings potential relative to greenhouse facility baseline lighting electricity usage is likely higher in greenhouses using LED fixtures due to their superior dimmability. Further investigation is recommended to quantify the energy saving potential of the technology in greenhouses using HPS lighting systems, which is the current greenhouse lighting standard practice throughout North America.

Another promising area of inquiry for future trials of the adaptive lighting controller is the potential for demand management. By utilizing the controller or other means to monitor instantaneous energy demand (kW) and automatically turn off or reduce output of the lighting system, greenhouse growers could participate in utility demand response programs. Adaptive lighting controllers could provide a mechanism to reduce greenhouse electricity demand without adversely impacting crop performance, and subsequently reduce peak demand charges for the greenhouse. Depending on the utility rate structure, reducing peak demand can result in significant energy cost savings.

The rate of adoption of this technology will depend on several factors including awareness among growers, availability of incentives, and the provision of non-energy benefits. The Candidus adaptive lighting controller tested has a relatively short simple payback period and is designed to be scalable, allowing growers to initially implement on a small scale and then expand the number of light fixtures being controlled. This makes it accessible to a wide range of greenhouse operations, from small low-tech to large high-tech facilities. While the Candidus controller is compatible with most LED and HID lighting manufacturers and fixture models, one potential limitation of this category of lighting controllers is incompatibility with HID fixtures, and/or incompatibility with certain lighting fixture models.

The overall response of Wheatfield Gardens to the adaptive lighting controller was entirely positive, and the company has expressed interest in expanding the use of this technology to other parts of the operation, including the hemp production area. The primary benefits of the technology to Wheatfield Gardens, beyond potential energy savings, are the monthly reports provided by the Candidus and the granular lighting system control provided by the technology. The combination of energy and non-energy benefits offered by this technology is a potentially important factor in driving adoption by greenhouse growers, where energy savings along may not be sufficient to motivate installation.

The potential for greenhouse adaptive lighting control technology is promising in terms of energy efficiency potential, enabling more granular control of greenhouse lighting systems, and providing convenience and increased energy data awareness to greenhouse growers. As the CEA industry continues to grow and significant horticultural lighting loads are added to the electric grid, this technology holds promise for a variety of stakeholders to help attain sustainability goals. As with any new or emerging agricultural energy efficiency technology, there will likely be significant barriers to adoption, which can be lessened by developing new trials, case studies, and demonstrations that establish confidence with greenhouse growers.

7 References

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Appendix A. Crop Monitoring Photos

A.1 Crop Cycle #1 Test Crop Photos

a) Crop Cycle #1. Site Visit #1 (1/15/20): Butterhead lettuce seedlings in test plot.

b) Crop Cycle #1. Site Visit #1 (1/15/20): Individual butterhead lettuce seedling in hydroponic pond (test plot).

c) Crop Cycle #1. Site Visit #2 (2/17/20): Butterhead lettuce head transplants (test plot).

d) Crop Cycle #1. Site Visit #2 (2/17/20): Butterhead lettuce head transplant close-up (test plot).

e) Crop Cycle #1. Site Visit #3 (3/6/20): Harvested butterhead lettuce in clamshell container (test plot).

f) Crop Cycle #1. Site Visit #3 (3/6/20): Harvested butterhead lettuce on digital scale (test plot).

A.9 Crop Cycle #1. Control Crop Photos

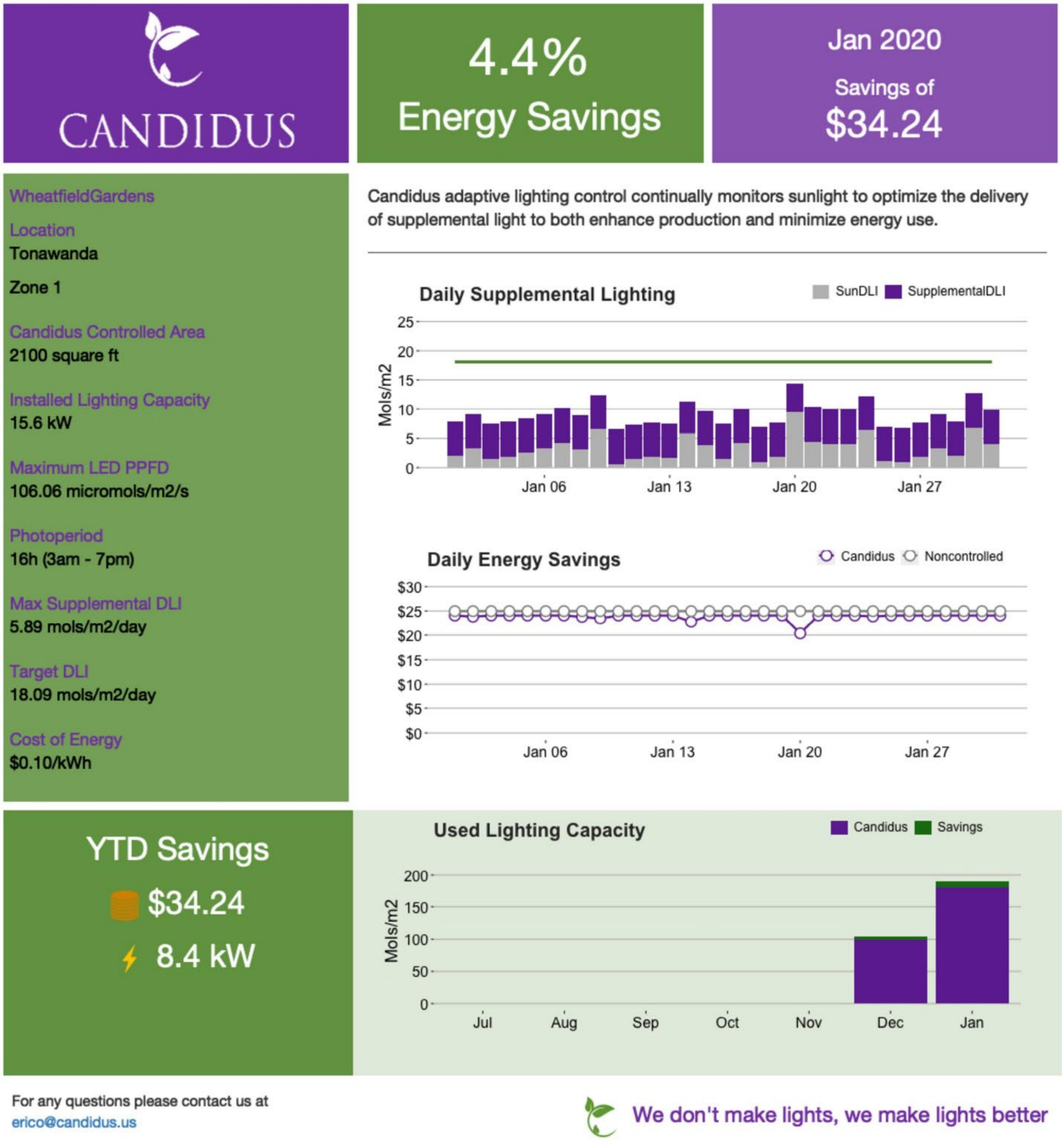
a) Crop Cycle #1. Site Visit #2 (2/17/20): Butterhead lettuce head transplants (control plot).

b) Crop Cycle #1. Site Visit #2 (2/17/20): Butterhead lettuce head individual transplant (control plot).

c) Crop Cycle #1. Site Visit #3 (3/6/20): Harvested butterhead lettuce in clamshell container (control plot).

d) Crop Cycle #1. Site Visit #3 (3/6/20): Harvested butterhead lettuce on digital scale (control plot).

Appendix B. Candidus Monthly Reports



CANDIDUS

4.4%

Energy Savings

Jan 2020

Savings of

$34.24

WheatfieldGardens

Location

Tonawanda

Zone 1

Candidus Controlled Area

2100 square ft

Installed Lighting Capacity

15.6 kW

Maximum LED PPFD

106.06 micromols/m2/s

Photoperiod

16h (3am - 7pm)

Max Supplemental DLI

5.89 mols/m2/day

Target DLI

18.09 mols/m2/day

Cost of Energy

$0.10/kWh

Candidus adaptive lighting control continually monitors sunlight to optimize the delivery of supplemental light to both enhance production and minimize energy use.

Daily Supplemental Lighting

Daily Energy Savings

YTD Savings

$34.24

8.4 kW

Used Lighting Capacity

For any questions please contact us at
erico@candidus.us

We don't make lights, we make lights better

CANDIDUS

14.8%
Energy Savings

Feb 2020

Savings of
$107.36

WheatfieldGardens

Location
Tonawanda

Zone 1

Candidus Controlled Area
2100 square ft

Installed Lighting Capacity
15.6 kW

Maximum LED PPFD
106.06 micromols/m2/s

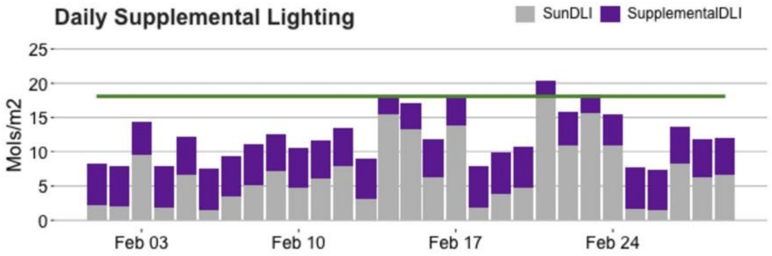
Photoperiod
16h (3am - 7pm)

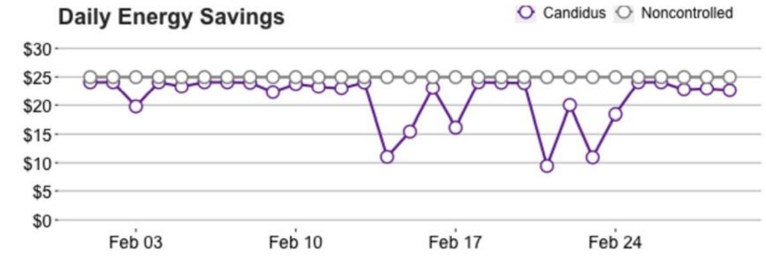
Max Supplemental DLI
5.89 mols/m2/day

Target DLI
18.09 mols/m2/day

Cost of Energy
$0.10/kWh

Candidus adaptive lighting control continually monitors sunlight to optimize the delivery of supplemental light to both enhance production and minimize energy use.

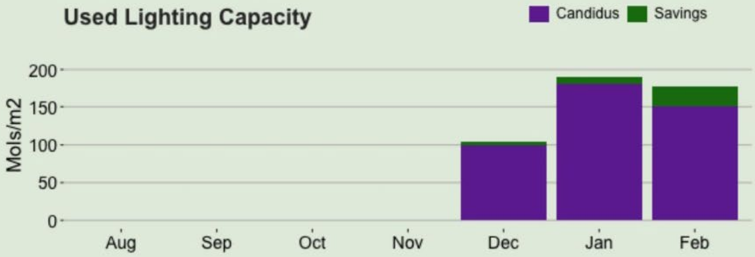




YTD Savings

$141.6

34.6 kW



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CANDIDUS

26.6%
Energy Savings

Mar 2020
Savings of
$206.06

WheatfieldGardens

Location
Tonawanda

Zone 1

Candidus Controlled Area
2100 square ft

Installed Lighting Capacity
15.6 kW

Maximum LED PPFD
106.06 micromols/m2/s

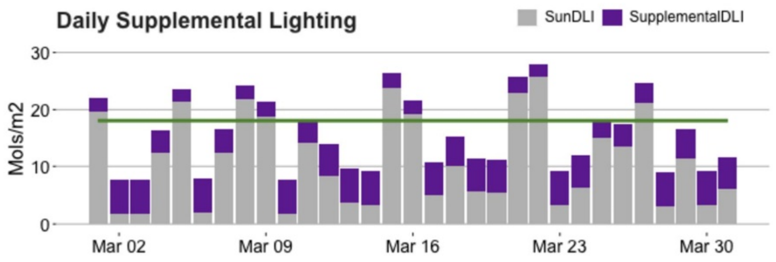
Photoperiod
16h (3am - 7pm)

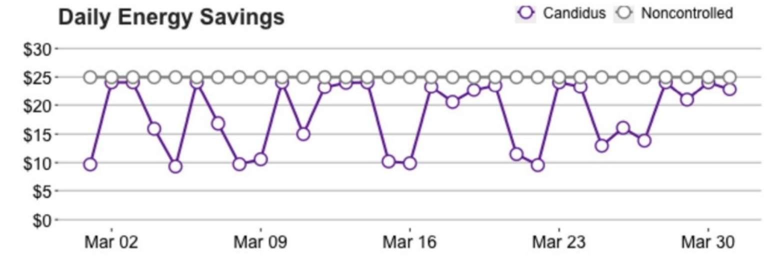
Max Supplemental DLI
5.89 mols/m2/day

Target DLI
18.09 mols/m2/day

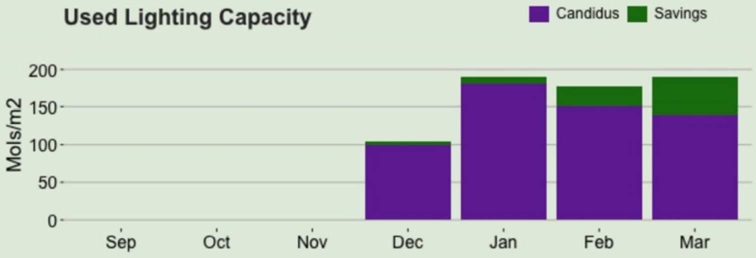
Cost of Energy
$0.10/kWh

Candidus adaptive lighting control continually monitors sunlight to optimize the delivery of supplemental light to both enhance production and minimize energy use.


Daily Supplemental Lighting


Daily Energy Savings

YTD Savings
$347.66
85 kW


Used Lighting Capacity

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CANDIDUS

44.6%
Energy Savings

Apr 2020

Savings of

$316.58

WheatfieldGardens

Location

Tonawanda

Zone 1

Candidus Controlled Area

2100 square ft

Installed Lighting Capacity

15.6 kW

Maximum LED PPFD

106.06 micromols/m2/s

Photoperiod

15h (4am - 7pm)

Max Supplemental DLI

6.11 mols/m2/day

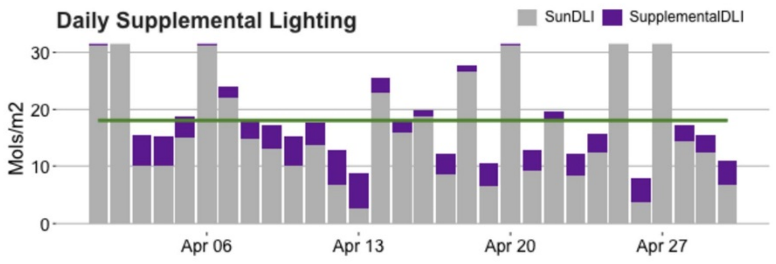
Target DLI

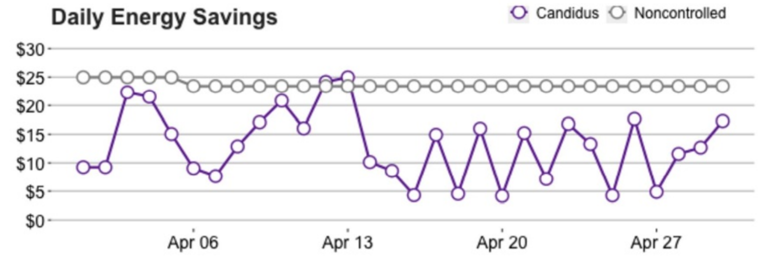
18.09 mols/m2/day

Cost of Energy

$0.10/kWh

Candidus adaptive lighting control continually monitors sunlight to optimize the delivery of supplemental light to both enhance production and minimize energy use.

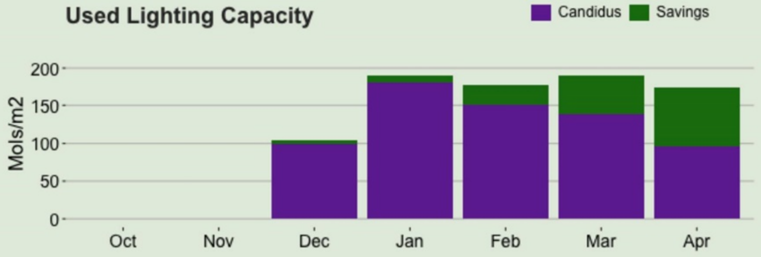




YTD Savings

$664.24

162.5 kW



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CANDIDUS

52.2%

Energy Savings

May 2020

Savings of

$378.36

WheatfieldGardens

Location
Tonawanda

Zone 1

Candidus Controlled Area
2100 square ft

Installed Lighting Capacity
15.6 kW

Maximum LED PPFD
106.06 micromols/m2/s

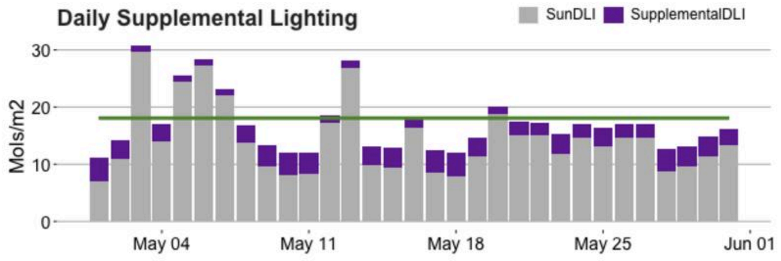
Photoperiod
15h (4am - 7pm)

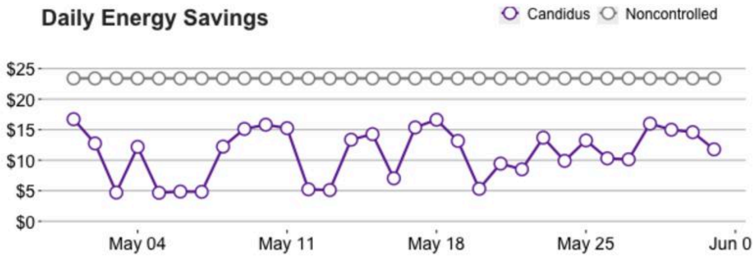
Max Supplemental DLI
4.09 mols/m2/day

Target DLI
18.09 mols/m2/day

Cost of Energy
$0.10/kWh

Candidus adaptive lighting control continually monitors sunlight to optimize the delivery of supplemental light to both enhance production and minimize energy use.

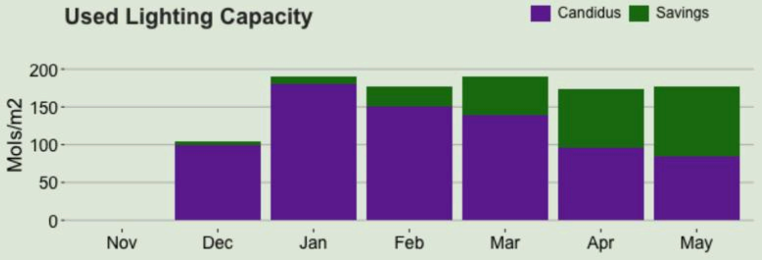

Daily Supplemental Lighting


Daily Energy Savings

YTD Savings

$1042.6

10171.2 kwh


Used Lighting Capacity

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CANDIDUS

42.3%
Energy Savings

Jun 2020
Savings of
$297.24

WheatfieldGardens

Location
Tonawanda

Zone 1

Candidus Controlled Area
2100 square ft

Installed Lighting Capacity
15.6 kW

Maximum LED PPFD
106.06 micromols/m2/s

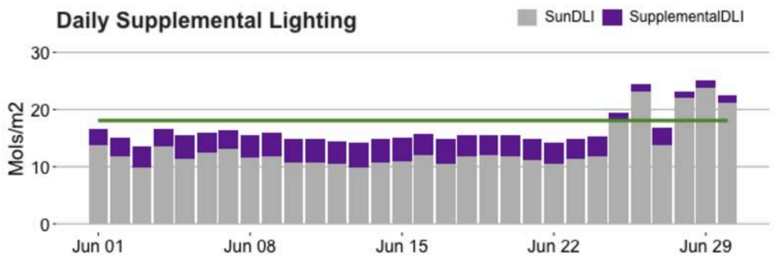
Photoperiod
15h (4am - 7pm)

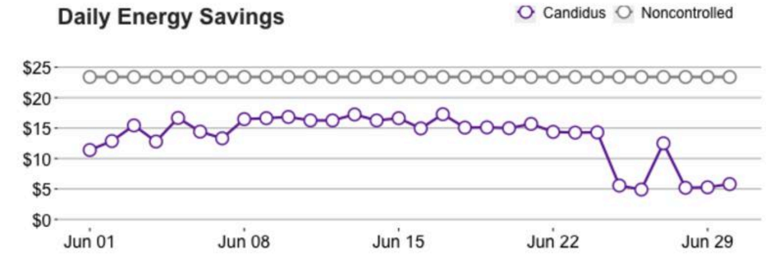
Max Supplemental DLI
4.23 mols/m2/day

Target DLI
18.09 mols/m2/day

Cost of Energy
$0.10/kWh

Candidus adaptive lighting control continually monitors sunlight to optimize the delivery of supplemental light to both enhance production and minimize energy use.

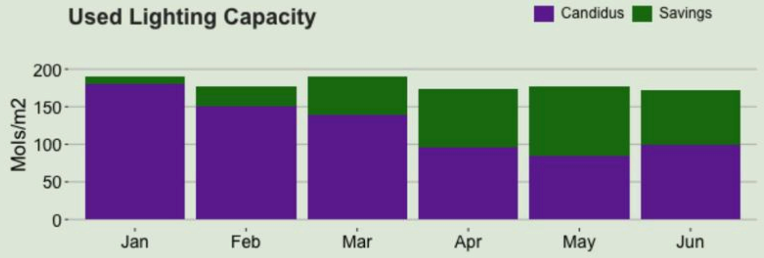

Daily Supplemental Lighting


Daily Energy Savings

YTD Savings

🪙 **$1339.84**

⚡ **13143.5 kwh**


Used Lighting Capacity

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CANDIDUS

63.2%
Energy Savings

Jul 2020

Savings of

$458.57

WheatfieldGardens

Location
Tonawanda

Zone 1

Candidus Controlled Area
2100 square ft

Installed Lighting Capacity
15.6 kW

Maximum LED PPFD
106.06 micromols/m2/s

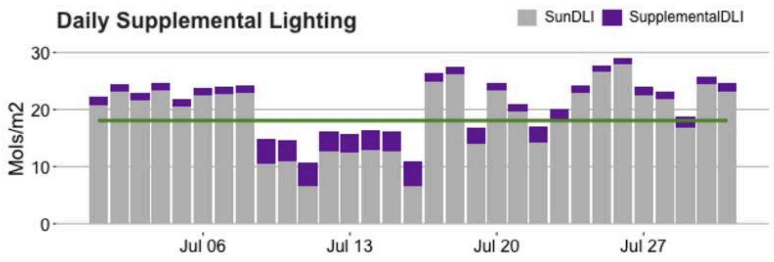
Photoperiod
15h (4am - 7pm)

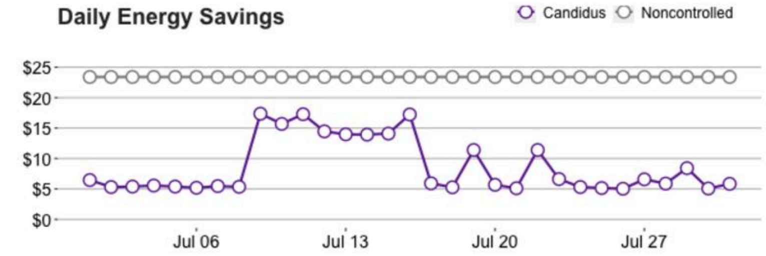
Max Supplemental DLI
4.25 mols/m2/day

Target DLI
18.09 mols/m2/day

Cost of Energy
$0.10/kWh

Candidus adaptive lighting control continually monitors sunlight to optimize the delivery of supplemental light to both enhance production and minimize energy use.

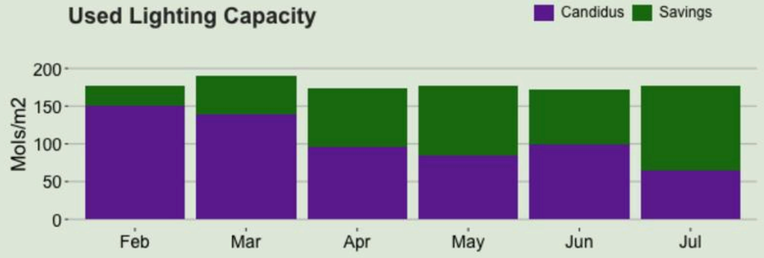

Daily Supplemental Lighting


Daily Energy Savings

YTD Savings

$1798.41

⚡ **17728.7 kwh**


Used Lighting Capacity

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