SmartAg Controls: Incentivizing Efficiency & Yields

Final Report

ET25SWE0034

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September 4, 2026

Program paid for by ratepayers.

Acknowledgements

The project team would like to thank the vendor for the lighting equipment and controls responsible for installation, commissioning, site recruitment, and site operational coordination. The team would also like to thank the site for hosting this field demonstration and for their ongoing support throughout the setup and baseline monitoring phases.

Executive Summary

This final report summarizes the findings, challenges, and recommendations from a field demonstration project evaluating daily light integral (DLI)–based smart lighting controls in commercial greenhouse operations. The authors of this report—referred to as the evaluation, measurement, and verification (EM&V) contractor team—conducted the third-party energy monitoring and verification, which included sensor selection, sensor installation, data collection, data analysis, and report writing. The vendor for the lighting equipment and DLI controls was responsible for site selection, site recruitment, installation, commissioning, and site operations coordination. The project aimed to assess whether advanced DLI-driven lighting controls could dynamically adjust light intensity and duration in response to real-time environmental conditions, improving energy efficiency without impacting crop productivity. While the project navigated commissioning and operational challenges that limited the ability to fully test DLI-based controls, the study provides valuable insights for future implementations, utility program designs, and California Title 24 code enhancements.

The primary objective of this study was to evaluate the energy savings, demand reduction potential, and crop productivity impacts of DLI-based lighting controls in real-world greenhouse conditions. The project also documents lessons learned, refines protocols for DLI-based optimization, and provides actionable recommendations to inform utility incentive programs and promote broader industry adoption.

This report reflects baseline development, DLI-based smart lighting controls system implementation, performance analysis, and stakeholder engagement. The project successfully documented lessons learned, provided interim data, and engaged stakeholders to ensure the findings are actionable and relevant for future deployments.

Key Findings

1. **Energy and Demand Impacts**

- Limitations on the vendor's ability to fully commission DLI controls for nighttime interruption operation prevented the evaluation of true energy savings and peak demand reductions.
- Baseline data revealed that lighting energy use and demand savings are crop-dependent, with certain crops requiring supplemental lighting only during winter months. This contrasts with Title 24 models, which assume year-round lighting use based on cannabis data.
- During a limited five-day operational period, the intervention lighting system demonstrated a 26 percent reduction in energy use compared to the baseline. However, this was due to site personnel manually shortening lighting durations irrespective of solar input, rather than DLI-driven control.

2. **Operational Challenges**

- Significant delays in installation and commissioning, coupled with equipment malfunctions, prevented the system from achieving its intended functionality.

- Grower and equipment misalignment on DLI implementation practices (nighttime interruption instead of the planned daylight extension), resistance to the complexity of the system, and reversion to manual timer-based controls.
- The site's decision to implement nighttime interruption lighting, rather than daylight extension as planned, further limited the system's ability to achieve clear energy and demand savings during peak grid capacity periods.

3. Crop Productivity and Environmental Conditions

- The study was unable to draw meaningful conclusions about crop impacts due to the lack of DLI control in the intervention greenhouse, the short intervention period duration, and uncontrolled production variables between the baseline and intervention greenhouses.

4. Stakeholder Feedback

- Stakeholders, including utility program managers and industry groups, expressed strong interest in the project's potential to provide empirical data on advanced lighting controls.
- Feedback emphasized the importance of credible field data to inform utility incentive programs, define codes and standards enhancements, refine cost-effectiveness models, and improve grower confidence in adopting emerging technologies.

Critical Recommendations

To further the project findings, the project team has made the following recommendations:

1. **Prioritize robust commissioning.** Define "commissioning complete" as the point at which the full control loop is verified and operational. Ensure commissioning is completed well in advance of the operational window of the specific site and crop to allow for troubleshooting and adjustments.
2. **Simplify system design and provide training.** Develop user-friendly systems and provide comprehensive training to growers to build confidence and reduce reliance on manual controls.
3. **Tailor programs to crop-specific needs.** Update Title 24 models and utility programs to reflect the variability in lighting requirements across different crops to improve program site recruitment targeting cost-effectiveness and market adoption.
4. **Investigate daylight extension.** Explore the energy and demand savings potential of daylight extension as an alternative to nighttime interruption, which may offer greater efficiency and fewer implementation challenges.
5. **Control environmental variables.** Standardize plant counts, schedules, and shading practices to isolate the effects of lighting interventions and improve data reliability. Site selection with identical operation commitments will be necessary for crop yield comparisons.

The project team has actively engaged stakeholders— including utility program managers, greenhouse operators, and industry groups—to share interim findings and gather feedback. These efforts aim to reduce uncertainty, accelerate market adoption, and support the integration of DLI-driven lighting controls into utility programs and codes. Ongoing outreach will include targeted discussions and the dissemination of best-practice guidelines that discuss how to navigate common pitfalls to facilitate broader industry adoption.

While the project faced challenges, it provided valuable insights into the complexities of implementing DLI-based lighting controls in commercial greenhouse environments. By addressing the lessons learned and recommendations outlined in this report, future efforts can achieve greater energy savings, demand reductions, and inform market adoption, supporting California's agricultural efficiency and climate goals.

Abbreviations and Acronyms

Acronym	Meaning
AESAP	Agriculture Energy Savings Action Plan
eTRM	Electronic Technical Reference Manual
CO_2	Carbon dioxide
DC	Direct current
DLI	Daily light integral
EM&V	Evaluation, measurement, and verification
IOU	Investor-owned utility
IPMVP	International Performance Measurement and Verification Protocol
kW	Kilowatt
kWh	Kilowatt hour
LED	Light-emitting diode
M&V	Measurement and verification
PAR	Photosynthetically active radiation
PG&E	Pacific Gas and Electric
PPFD	Photosynthetic photon flux density
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
TOU	Time-of-use

Contents

Tables

Figures

Introduction

This report provides results from a field demonstration research project evaluating daily light integral (DLI)–based smart lighting controls in commercial greenhouse operations. The authors of this report were responsible for third-party energy monitoring and verification, including sensor selection, sensor installation, data collection, data analysis, and report writing. The vendor for the lighting equipment and DLI controls was responsible for site selection, site recruitment, installation, commissioning, and site operations coordination. The project team designed the study to evaluate whether advanced DLI-based smart lighting controls' ability to adjust light intensity in response to real-time environmental conditions could improve energy performance without negatively affecting crop productivity. While the project did not demonstrate the expected DLI-control outcomes due to commissioning and operational challenges, this report presents data collected, valuable insights, and subsequent recommendations.

The primary objectives of this field demonstration were to quantify the lighting energy savings, demand impacts, and crop yield impacts associated with DLI lighting controls. Specifically, the project aimed to verify percent reduction in lighting energy use, demonstrate potential for peak demand reduction through dynamic load management, and quantify impacts in crop metrics (e.g., yield observations, waste, etc.). The project serves to document lessons learned, with a goal of informing utility program design and California Title 24 codes and standards related to greenhouse lighting controls and support broader adoption of DLI-based lighting control systems across California's greenhouse industry.

This report summarizes baseline conditions, project activities, site setup details, metering infrastructure, data collection, data analysis methodologies, and energy impact findings. It also documents environmental conditions, crop production, lighting system details, and guidance for setting up and evaluating DLI-based lighting controls.

Establishing a baseline was critical for accurately quantifying the impacts of DLI-based control strategies. The findings provide the foundation for validating the energy and productivity benefits of advanced greenhouse lighting controls and ensuring credible, replicable results. The documentation of site conditions, measurement protocols, and data collection methods will also support future demonstrations and inform the development of more targeted and robust measurement and verification (M&V) approaches for utility energy efficiency programs, as well as inform codes and standards assumptions.

To enable precise evaluation of DLI-based control performance, the project team installed electrical power submetering infrastructure and environmental sensors capable of measuring lighting energy use, photosynthetic photon flux density (PPFD), temperature, humidity, and carbon dioxide (CO_2) concentration. The site manager provided crop metrics, including yield and waste, to establish baseline performance and assess impacts of DLI-driven control.

This report is organized as follows:

Background: Provides a summary of the project's goals, partners, and relevance to California's agricultural efficiency priorities.

Objectives: Outlines the objectives of the field demonstration.

Methodology and Approach: Summarizes the methodology, including site selection, baseline development, metering setup, and data analysis approach details.

Data Processing

The EM&V contractor began by compiling and aligning all the data from the various meters and sensors. The research team reviewed changes that could have an impact on the data collected and decided how the changes should be handled during the data analysis process. Table 2 presents the events and the actions we took.

Table 2: Event log and data impacts.

Start Date	End Date	Action	Reason	Days Impacted
1/8/2026	1/13/2026	Dropped existing light power/energy data	"E-72 Zone 1 operated at reduced power (~30%) for approximately five days. The site operator performed manual resets. The symptoms were consistent with an intermittent fault in the vendor supplied timer/contactor (the same component that later failed on 2026-03-11)" per the documentation provided by the lighting installers.	5
2/2/2026	2/5/2026	Dropped new light power/energy data	New lights initial installation day and breaker trip followed by make-up lighting	3
2/9/2026	2/14/2026	Dropped new light power/energy data	New lights additional breaker trip and atypical lighting operation	5
2/21/2026	2/26/2026	Dropped new light power/energy data	New lights additional breaker trip and atypical lighting operation. "short-circuit condition in the DC daisy-chain wiring" per the documentation provided by the lighting installers.	5

Note: Representations of the raw data—e.g., time series of raw power data—include the dropped data above. The team dropped the dates above in summary plots and tables.

The team created visualizations to review the raw data for any significant outliers, and the data were found to fall within reasonable bounds.

Data Analysis

The following formulas were used to calculate energy and demand savings.

- Energy savings (kWh):

$$Energy\ Savings\ (kWh) = \ (Baseline\ Power\ (kW) - Post\ Intervention\ Power\ (kW))$$

- Demand savings (kW):

$$Demand\ Savings\ (kW) = Basline\ Power\ (kW\ Peak) - Post\ Intervention\ Power\ (kW\ peak)$$

Peak demand was calculated according to the Design Energy Efficiency Rating method for calculating peak demand reductions, which uses an estimated average grid level impact for a measure between 4:00 p.m. and 9:00 p.m. during a “heat wave.” It was defined after the fact by identifying the three consecutive weekdays with the hottest weather conditions that are expected to produce a regional grid peak event; peak days for Climate Zone 10 are June 26 through July 1. However, it is important to note that the study window occurred during the winter months, which did not overlap with the identified peak window. As a result, the peak demand reductions calculated in this study are based on modeled assumptions rather than direct measurements during peak demand days. This limitation should be considered when interpreting the demand savings results, as they may not fully reflect real-world peak conditions.

In real-world greenhouse operations, demand impacts can vary significantly depending on the crop type and DLI target. For example, certain crops—such as petunias, snapdragons, dianthus, and poinsettias—do not require supplemental lighting at all during non-winter months. In contrast, crops like cannabis and tomatoes often require DLI-controlled supplemental lighting year-round, including during summer months. This variability means that the demand impact of greenhouse lighting controls depends heavily on the specific crop being grown and its lighting requirements.

We attempted to normalize savings for operational changes such as crop mix or production shifts, but there were prolonged periods where the intervention greenhouse was not operational, which prevented a normalized comparison. Based on the definition of the peak demand period not overlapping with the nighttime interruption light operation, the study did not find peak demand or TOU savings. However, future projects can use the nighttime interruption load shape measured in this study to inform California Energy Data and Reporting System for cost-effectiveness calculations across greenhouses with different crop types.

: Presents findings from the observation period, including baseline characterization, detailed results, data analysis, and stakeholder feedback.

Recommendations: Provides suggested next steps and further stakeholder engagement.

Background

California’s greenhouse industry represents a rapidly evolving segment of the state’s agricultural economy, increasingly shaped by pressures to reduce energy use, lower operating costs, and maintain year-round production in the face of tightening resource constraints. Supplemental lighting plays a significant role in achieving consistent crop yields, particularly during periods of low natural sunlight. However, conventional lighting systems—which often operate on fixed schedules or simple threshold controls—can lead to over-illumination, excessive energy consumption, and high peak electricity demand. As utilities and growers alike seek solutions to improve efficiency and reduce utility bills, advanced lighting control strategies based on the DLI have emerged as a promising pathway.

Technical Overview of DLI-Based Lighting Controls

DLI represents the total quantity of photosynthetically active radiation (PAR) received by plants over a 24-hour period. In horticultural lighting standards, PPFD is defined as the photon flux within the PAR wavelength band, from 400 nanometers (nm) to 700 nm. PPFD does not include radiation outside this range (e.g., ultraviolet or far-red). This distinction is important because some growers use the term "PPFD" informally to refer to total light intensity from all wavelengths. However, under formal American Society of Agricultural and Biological Engineers and DesignLights Consortium horticultural lighting definitions, PPFD is strictly limited to photons in the PAR band, and this is the definition used for all metering and analysis in this project.

Unlike static lighting schedules, DLI-based controls use environmental sensors to measure incoming sunlight and dynamically adjust artificial lighting output to ensure that each crop receives its optimal daily light dose. The system under evaluation in this field demonstration is specified by the vendor to have additional functionality with DLI-based smart lighting controls that can coordinate lighting intensity and duration in real time. By optimizing lighting inputs based on actual plant light needs, weather conditions, and growth stage, these controls aim to reduce energy consumption while maintaining or enhancing crop yield and quality. Some advanced industry solutions use DLI-based algorithms to adjust both light intensity and spectral composition in real time. In contrast, this CalNEXT field demonstration focused on controlling only the duration of lighting to evaluate energy savings. Future projects could explore the impact of controlling both spectral composition and light intensity.

Prior Research and Foundations

Several research studies and pilot projects have demonstrated the potential benefits of precision lighting control in greenhouse environments (Mosharafian, 2020) (Zhang, 2025) (Rengasamy, 2022) (Elkins, 2020) (Mattson, 2020). Laboratory-scale experiments and limited field trials have shown that integrating photosensors with dynamic control algorithms can reduce energy consumed by supplemental lighting by approximately 20 percent without negatively affecting crop production (van Iersel, 2016) , and studies at institutions such as Purdue have further highlighted the importance of DLI optimization for maintaining consistent yields across varying seasonal light conditions (Torres, 2025). However, most existing demonstrations have been conducted under controlled research settings or in operational settings using only simplified on/off control schemes. Few have incorporated DLI-driven management or continuous, real-world monitoring using International Performance Measurement and Verification Protocol (IPMVP) Option B protocols.

This project conducted a full-scale, side-by-side demonstration at an operating commercial greenhouse facility in California. While the project attempted to test DLI-driven controls, commissioning and operational challenges only allowed for the testing of more simplified timing controls dictated by site operations managers to control the timing of order delivery rather than optimize the amount of sunlight received based on DLI.

Market and Industry Context

Over the past decade, California's greenhouse sector has seen rapid adoption of light-emitting diode (LED) lighting, driven by declining equipment costs, improvements in fixture efficacy, growing awareness of energy efficiency incentives available through investor-owned utilities (IOUs), and more recently, code requirements. Still, despite these advances, most growers continue to operate lighting systems with limited control sophistication, typically relying on manual, time-based scheduling or basic instantaneous light sensors/threshold controllers that react to momentary intensity but do not track or control based on cumulative daily light. This lack of precision contributes to unnecessary energy use, elevates operating costs, and misses the opportunities for load management during peak demand periods.

The transition to smart lighting controls has been slower than anticipated, largely due to three persistent market barriers:

- Uncertainty about real-world performance and return on investment.
- Limited availability of verified field data quantifying both energy and crop impacts.
- Added technical complexity associated with implementing advanced controls in active greenhouse operations.

This field demonstration directly addressed these barriers by generating empirical evidence of performance in commercial growing conditions, using rigorous M&V methods.

Economic and Regulatory Drivers

California's broader energy and climate policy landscape provides strong motivation for demonstrating technologies that reduce electricity consumption and support greenhouse gas reductions through both efficiency programs, as well as codes and standards. Greenhouses, though a relatively small portion of total agricultural energy use, represent a significant opportunity for cost-effective energy savings and demand flexibility due to their high-intensity lighting loads. Utility programs such as Pacific Gas & Electric (PG&E)'s Agriculture Energy Savings Action Plan (AESAP), Southern California Edison (SCE)'s Agriculture Energy Efficiency Program, and San Diego Gas & Electric (SDG&E)'s Streamlined Ag Efficiency Program all emphasize lighting efficiency and demand response as priority measures. Additionally, proposed codes and standards enhancements aim to expand beyond LED lighting efficacy by including DLI-based greenhouse lighting controls in the next code cycle. Data from this project can help update California IOU agricultural programs by supporting the adoption of DLI-based controls as incentivized technologies and refine the assumptions used in the proposed code enhancement model.

Contribution to Technology Development

By demonstrating DLI-based smart lighting controls in operating commercial greenhouses, this project has provided valuable learnings that bridge the gap between laboratory research and scalable, market-ready solutions. The findings highlight the potential for energy savings with advanced lighting systems. Due to vendor and site commissioning and operational challenges, the lights were not controlled based on the amount of sunlight the plants received during the photoperiod. As a result, the project did not fully test DLI-driven lighting controls, limiting conclusions about the lighting controls integration with energy saving objectives and impact on grower productivity. The project offers insights for the development of practical M&V approaches that streamline program participation for growers, reduce administrative complexity for utilities, and help inform model assumptions of codes and standards.

In this context, the DLI-based lighting control demonstration serves not only as a technical validation of an emerging clean energy solution, but also a key step toward establishing industry best practices that can accelerate California's transition to efficient, data-driven, and economically resilient greenhouse operations.

Objectives

The primary objective of this field demonstration was to evaluate the performance and benefits of advanced DLI-based smart lighting controls in commercial greenhouse operations under real-world growing conditions. The study sought to determine whether DLI-driven lighting strategies can provide measurable reductions in lighting energy use while maintaining or improving crop yields.

The field demonstration was guided by the following research questions:

- How do DLI-based lighting controls affect total lighting energy consumption and peak demand compared to conventional lighting operation?
- To what extent can precision light management improve crop productivity and quality?
- What operational, behavioral, or environmental factors influence the performance and adoption of DLI-based greenhouse lighting systems?

Through rigorous M&V that followed IPMVP Option B protocols, the project aimed to generate quantitative evidence on energy and crop performance that can support the future inclusion of advanced lighting controls in California utility efficiency programs.

The specific goals of the study were to:

- Quantify baseline and post-installation lighting energy consumption at each greenhouse, expressed in kilowatt-hours and impact profiles.
- Document the system's ability to shift or reduce electrical demand during grid capacity periods.
- Evaluate crop yield and quality under optimized DLI control relative to baseline conditions.
- Identify operational and installation lessons that can inform best practices for future deployments.
- Develop recommendations for utilities, growers, and program implementers on how to integrate DLI-based lighting controls into incentive programs and on-farm management strategies.

The desired outcomes of this project included verified performance data, project cost impacts, and actionable recommendations to guide future program design. Additionally, while not a stated objective, the findings also revealed valuable insights that could help refine models used in proposed code enhancements.

Technology Transfer and Outreach

The recommendations developed in this study target California's agricultural energy efficiency programs and the broader greenhouse industry. Primary recipients include IOUs such as PG&E, SCE, and SDG&E, as well as agricultural program implementers and greenhouse operators. These results will be communicated through emailed project reports, stakeholder discussions, and a planned industry presentation, to ensure findings are accessible to both technical audiences and growers. By providing validated performance data and implementation guidance, this project aims to reduce uncertainty, accelerate market adoption, and support continued innovation in intelligent greenhouse lighting control technologies.

Methodology and Approach

The field demonstration study employed a controlled experimental design to evaluate the impact of advanced DLI-based greenhouse lighting controls on energy consumption, peak demand, and crop productivity. The methodology is intended to ensure transparency, reproducibility, and M&V in accordance with the IPMVP Option B framework.

Overall Experimental Design

The study design for the field demonstration recommended a control group design, comparing two adjacent greenhouses that the site staff described as having equivalent operations: one serving as a baseline control using conventional mechanical timer-controlled LED lighting system, and the other as an intervention greenhouse intended to be equipped with advanced daylight harvesting lighting controls on the same LED lighting. This design allowed for direct comparison of energy usage, environmental conditions, and crop outcomes between the two groups while minimizing confounding factors.

Key components of the experimental design included:

- **A single independent variable:** Lighting control strategy (mechanical timer vs. proposed DLI-based smart lighting controls).
- **Dependent variables:** Electrical energy consumption in kilowatt-hours (kWh), peak demand in kilowatts (kW), temperature, relative humidity, PPFD, CO_2 concentration, and crop yield/quality metrics.
- **Control factors:** Greenhouse size, crop type, planting schedule, and allocation of customer orders.
- **Monitoring interval:** Ten minutes for all environmental measurement and one minute for energy metrics.
- **Monitoring period**: Mid-November through mid-March, capturing seasonal variations and maximum supplemental lighting use.

The team selected the technology based on a vendor specification that noted it would be capable of dynamically optimizing light intensity and timing according to environmental conditions and target DLI levels. This selection reflects both the commercial availability of the system and its potential for measurable energy savings and productivity improvements in greenhouse operations. It is important to note that the demonstration did not show the selected technologies' capability of DLI controls, and that the control sequences we observed did not show lighting patterns that optimized light intensity or the timing of spectral output; therefore, it did not react to environmental conditions or adjust to reach target DLI levels, as the test plan below proposed. The challenges and deviations from the recommended study plan are addressed in this section.

Test Site

The field demonstration was conducted on site at a greenhouse in California Climate Zone 10. The facility contained multiple production greenhouses used for ornamental plant cultivation, including greenhouse E-72 (control) and greenhouse E-70 (intervention). Both greenhouses were of equal size (180 feet by 92 feet) and were both used to grow the same types of crops, which included petunias, snapdragons, dianthus, and poinsettias during the supplemental lighting season from mid-October to mid-March.

Baseline System (Control—Greenhouse E-72)

- Contained 108 CTF50 LED fixtures with on/off control.
- Fixture runtime was managed with mechanical timers, one per side of the greenhouse (54 fixtures each on the north and south).
- Served as the reference for conventional LED operation without DLI control integration.

Proposed System (Intervention--Greenhouse E-70)

- Contained 108 new DLI-Touch LED fixtures equipped with capabilities for DLI-based smart lighting controls.
- The control system intended to adjust light intensity according to photosynthetic light levels to maintain desired DLI targets.
- The team recommended customer orders be split evenly between both greenhouses to maintain comparable product mix and operating conditions. Over the course of the field period, the site operations manager's decisions led to a significantly larger number of plants cultivated in the greenhouse E-70 (control) than greenhouse E-72 (intervention).

Independent Variables and Site Characteristics

- **Site greenhouse area:** 16,560 square feet
- **Climate Zone:** 10
- **Crops:** Petunias, snapdragons, dianthus, and poinsettias
- **Lighting control type:** Fixed vs. DLI-based
- **Monitoring period:** Mid-November through mid-March
- **Monitoring interval:** 10 minutes for environmental sensors and one minute for lighting energy
- **Site photographs:** Below, we have included pictures of the greenhouse facility, DLI, metering set up, and the heating unit (Figure 1 through Figure 7).

Figure 1: Outside view of greenhouse facility.

Figure 2: Inside view of control greenhouse (E-72).

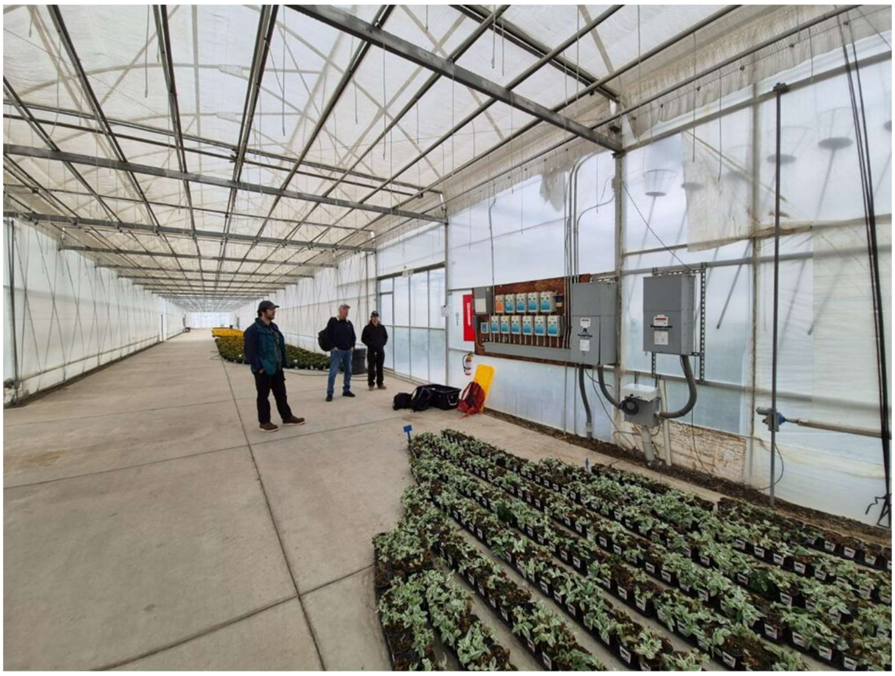

Figure 3: Inside view of electrical panel in hallway between greenhouses.

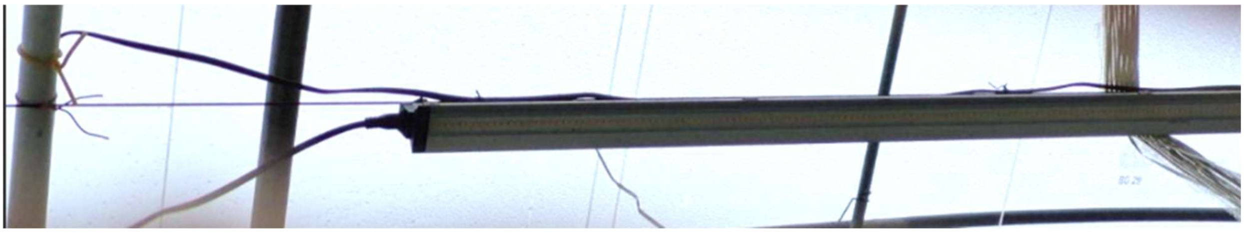

Figure 4: Baseline LED lighting.

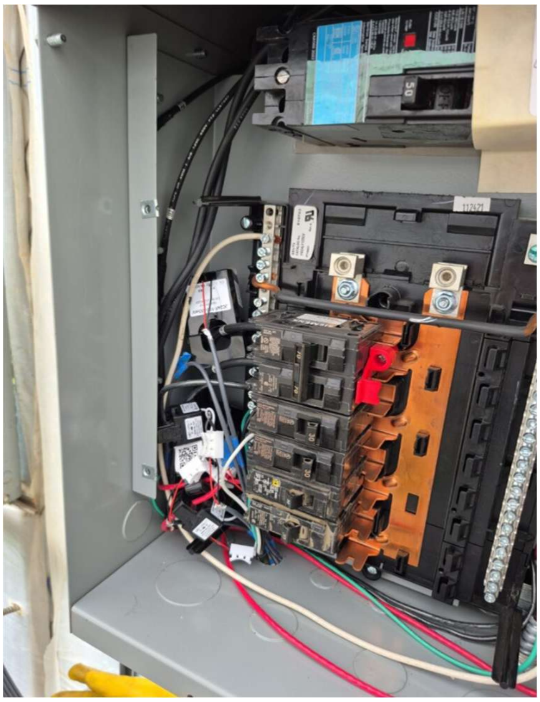

Figure 5: Sample of circuit level metering.

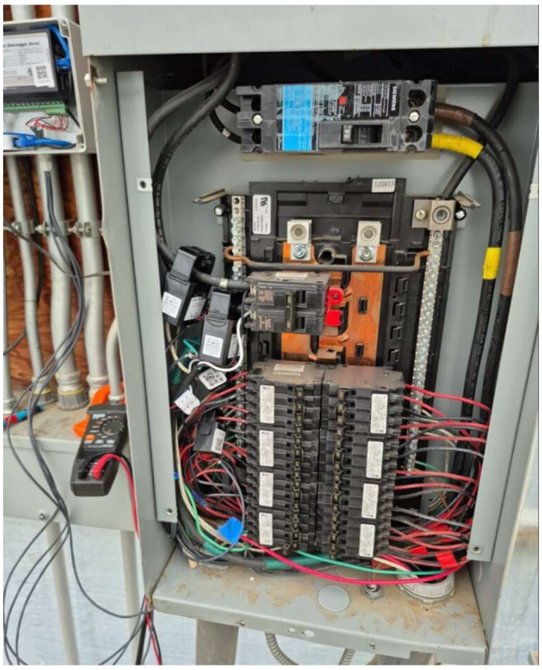

Figure 6: Additional metering.

Figure 7: Greenhouse heating unit.

Proposed Field Demonstration Procedure

The field demonstration planned for sequential steps to ensure consistent, accurate data collection and minimize disruption to normal operations. The following procedure is listed as it was proposed, and not as was realized within the project's study period due to commissioning and operational challenges.

Baseline vs. Intervention Case Measurement

- Establish the monitoring infrastructure in the baseline greenhouse (E-72) and intervention greenhouse (E-70) using eGauge power meters and environmental sensors.
- Baseline greenhouse (E-72) to serve as the control group and intervention greenhouse (E-70) to serve as the experimental group in this side-by-side experimental design. All greenhouse operational and design details, besides the lighting, will be consistent for both greenhouses. Non-routine events that cause divergence in operation or design of either greenhouse are to be monitored and reported. Recorded energy usage, environmental parameters, and crop metrics over a three- to five-month period will be used to compare baseline conditions to intervention conditions in side-by-side greenhouses throughout the seasonal variations of daylight.

Intervention Preparation

- Prepare intervention greenhouse (E-70) for advanced lighting installation, including layout verification, wiring, and sensor placement.
- Conduct safety inspections and ensure all installation procedures comply with electrical and operational safety standards.

Technology Installation

- Install the LED fixtures with DLI-driven controls in E-70.
- Verify system functionality. Full system functionality would have implemented a daylight extension approach to dynamic dimming or timing adjustments in response to solar input through integration with environmental sensors.

Operational Monitoring

- Continuously collect data on power, environmental parameters, and crop growth post-installation.
- Maintain consistent operational schedules and customer order distribution across both greenhouses to control for operational variability.

Interim Analysis and Quality Checks

- The vendor conducted site visits to observe and validate system performance. The evaluation, measurement, and verification (EM&V) team calibrated and installed measurement instruments, as well as analyzed meter data.
- During periodic data checks, the EM&V contractor alerted the vendor of unexpected meter readings. The vendor worked with site operators to try to correct the identified unexpected meter readings by attempting to resolve a variety of operational challenges, such as malfunctions, deviations in operating hours, and unexpected environmental changes.

Data Preparation for Analysis

- The EM&V contractor team aggregated and cleaned datasets.
- The EM&V contractor team prepared descriptive statistics and performed statistical analysis where possible.

Documentation of Results and Technology Transfer

- The EM&V contractor team recorded findings.
- The EM&V contractor and vendor prepared guidance for stakeholders, including utility program managers and growers, to support further adoption or replication of advanced lighting controls.
- The EM&V contractor and vendor teams collaboratively documented operational lessons learned and safety practices to inform future implementations.

By planning the field demonstration in this manner, the methodology attempted to ensure that energy savings, peak demand reductions, and crop performance impacts could be rigorously quantified and verified, providing actionable insights for both utility programs and commercial greenhouse operators. However, due to a combination of commissioning challenges and site operational challenges, the realized field demonstration procedure differed significantly from the planned demonstration procedure. The next section discusses the procedure the vendor and EM&V contractor team pivoted to in response to the operational and commissioning challenges.

Realized Field Demonstration Procedure

Changes from the proposed test plan resulted from operational and commissioning challenges, which included coordination challenges, equipment malfunction, and failure to demonstrate DLI-control capabilities within the study period. The changes and reasons for test plan adaptation are described in this section. The test plan maintained the control group study design, comparing energy performance and crop outcomes between the baseline and intervention greenhouses and IPMVP Option B protocol. However, there were substantial barriers to validating the asserted energy savings and functionality of the new DLI-controlled lighting system. Due to the site operations' mismanagement of control variables, the plant quality and yield metrics were compromised.

Baseline vs. Intervention Case Measurement

The baseline greenhouse (E-72) served as the control group and intervention greenhouse (E-70) served as the experimental group in a side-by-side experimental design. The number of plants produced in the baseline greenhouse was much larger than that of the intervention greenhouse due to the delay of the advanced lighting in shipping, installation, and commissioning. This difference in plant count impacted other operational factors—such as watering and heating cycles—as the baseline greenhouse (E-72) was operational while the intervention greenhouse (E-70) was non-operational for months. In this manner, lighting was not the only independent variable as originally intended. Additionally, there were several non-routine events (i.e., tripped breakers) that impacted the lighting operations in both greenhouses.

While the study design intended to compare baseline conditions to intervention conditions in side-by-side greenhouses—with the site completing commissioning in November and monitoring to occur from December to April—commissioning delays shortened the recorded energy usage, environmental parameters, and crop metrics to only a five-day period at the end of the supplemental lighting season. Therefore, the intended understanding of the adaptation and DLI-control impacts of the seasonal variations of daylight were not realized. Shipping delays, scheduling conflicts, equipment malfunction, and misunderstanding about the type of supplemental lighting that was to be provided (nighttime interruption, not daylight extension) led to substantial delays. The lighting implementors were prepared to commission the lighting for daylight extension supplemental lighting patterns; supplemental lighting is intended to extend daylight in seasons where there is less natural sunlight.

However, the test site operated using nighttime interruption supplemental lighting. Greenhouse E-72 (baseline) primarily had supplemental lighting—controlled on/off controls with mechanical timers between the hours of 10:00 p.m. and 4:00 a.m.—that delivered a level of light the grower believes wakes the plants up at night. Those nighttime levels were not related to the amount of light the plants received during the day—a misunderstanding that created significant commissioning delays. The PPFD sensors that drive the new advanced lighting DLI-controls were not easily adjusted to effectively measure PPFD during nighttime when there is almost no natural sunlight. These delays shortened the "fully commissioned" period to only five days in mid-March at the end of the supplemental lighting season. Due to the delays in commissioning, crop production, energy use, and environmental metrics the project team found not related to DLI-driven controls, the lights were never controlled based on the amount of sunlight received.

Intervention Preparation

Preparing for the intervention lighting saw no changes from the proposed test plan.

Technology Installation

The team installed LED fixtures with DLI controls in greenhouse E-70 (intervention), but no true DLI controls were ever successfully implemented.

The site implemented a nighttime interruption strategy optimized for timing the delivery of crops (irrespective of solar input) instead of a daylight extension strategy optimized for reaching a DLI target. In practice, the grower prioritized maintaining their established approach to managing flowering and harvest windows, which relies on fixed nighttime lighting schedules. Although the DLI-controlled system was designed to be capable of adjusting lighting based on solar input to achieve a target DLI through daylight extension, the grower operated the new lights using a set nighttime schedule (i.e., a fixed amount of light per night) instead of dynamically modulating light levels in response to daylight. This choice reflected the grower's business objectives and existing operational practices, and it limited the extent to which the demonstration could evaluate DLI-based daylight extension as originally envisioned.

We were only able to verify a small portion of the system functionality (manual timing adjustment only). Full system functionality would have included dynamic dimming in response to the amount of sunlight received, spectral control, and integration with environmental sensors. The new LED fixtures installed in greenhouse E-70 only exhibited manual duration-based controls during the five-day "fully commissioned" demonstration period. Dimming was only demonstrated during a period of manual intervention; therefore, the team could not adequately study data representative of dynamic dimming, spectral control, environmental sensor integration, or DLI-based controls.

Operational Monitoring

- Data on power, environmental parameters, and crop growth post-installation were collected continuously.
- Inconsistencies in operational schedules and customer order distribution across both greenhouses led to operational variability that was addressed during data analysis.

Interim Analysis and Quality Checks

- The team performed interim analysis and quality checks as described in the methodology.

Data Preparation for Analysis

- The team prepared data for analysis as described in the methodology.

Documentation of Results and Technology Transfer

- The team documented results and transferred technology findings as described in the methodology.

Data Collection and Instrumentation

The team targeted the following metrics to quantify lighting function and potential for energy cost savings during the field demonstration:

1. **Natural sunlight (PAR):** PAR data was collected inside and outside the greenhouse. Each grow room was controlled by a single light sensor.
2. **Target DLI:** Crop-dependent DLI requirements were specified as the control threshold. Plants grown during the study included petunias, snapdragons, dianthus, and poinsettias, with a recommended DLI of 10 moles per square meter per day to 12 moles per square meter per day.

3. **Fixture specifications:** The control greenhouse used LED strip fixtures rated at 50 watts and 2.1 micromoles per joule, while the intervention greenhouse used similar fixtures rated at 50 watts and 2.5 micromoles per joule.
4. **On/off schedule:** The baseline fixtures operated on a fixed schedule (10:00 p.m. to 4:00 a.m.), consistent with the metered power output.
5. **Dynamic lighting hours:** The intervention lighting system was never fully commissioned to control light intensity, duration, or spectrum based on natural sunlight received the previous day. Instead, the lights were manually set to a fixed timer schedule.
6. **Dimming levels:** Real-time power consumption data were collected for both greenhouses. The intervention lights did not autonomously dim, and instances of dimming were observed only through manual intervention.
7. **Sensor logs:** PAR sensors tracked the cumulative PAR moles of light delivered throughout the photoperiod. However, the sensors were calibrated for the planned daylight extension operation and were not calibrated for low-light conditions in nighttime interruption.
8. **Energy consumption:** Energy consumption was measured for both grow rooms.
9. **Time-of-use (TOU) rates:** Electricity cost structures were considered, but baseline and intervention supplemental lighting occurred at night. Therefore, the TOU rate or peak demand analysis was inconclusive.

Table 1 summarizes the monitoring equipment used to collect power and environmental data.

Table 1: Data collection parameters and instrumentation.

Parameter	Instrument	Model	Provider
Power (kW)	eGauge	EG4015, JS16FL-100-333mV	Research team
Temperature (°F)	Aranet	TDSPT8U2	Project team
Relative Humidity (%RH)	Aranet	TDSPT8U2	Project team
PPFD (µmol/ft^2)	Aranet	TDSKARU2	Project team
CO2 (PPM)	Aranet	TDSPCOU5	Project team

Quality Assurance and Risk Management

The project team worked with the site operators to perform on-site verification to ensure equipment calibration and consistency with design specifications. However, it should be noted that PPFD sensors were not in place during the metering installation and, therefore, could not be validated. As a result, the focus of the analysis was on relative values between the two greenhouses rather than absolute PPFD measurements. This approach aligns with the project's primary interest in comparing performance differences rather than relying on precise PPFD values.

Potential risks included:

- Malfunctioning lighting controls
- Inaccurate baseline data
- Shifts in operational hours or crop scheduling

The team attempted to mitigate these issues through remote monitoring, coordination with site staff, and periodic inspection of monitored parameters. Risk management posed a large challenge over the course of the metered study period, with operational and control decisions not communicated to the EM&V team until it was too late to adjust. One notable challenge was related to the site master grower's decision to use nighttime interruption instead of daylight extension. The PPFD sensor selection and calibration were intended for high light levels in daylight extension operation. Switching from the planned test to nighttime interruption operated the lights with much lower light levels below the calibration range of the sensors reducing accuracy.

Additionally, the master grower's approach to the nighttime extension schedule was based on meeting a fixed duration each night rather than adjusting lighting duration in relation to the amount of sunlight the plants received during the day, so DLI control operation could not be measured or verified. These factors resulted in a large deviation from the proposed demonstration and study plan to achieve the planned results. However, the results we collected provided insights into the challenges of implementing DLI-based lighting controls in real-world greenhouse operations.

Data Analysis Methodology

The research team processed and analyzed the data after a thorough review of events to best represent the data collected and extract insightful findings. This section describes this process.

Data Processing

The EM&V contractor began by compiling and aligning all the data from the various meters and sensors. The research team reviewed changes that could have an impact on the data collected and decided how the changes should be handled during the data analysis process. Table 2 presents the events and the actions we took.

Table 2: Event log and data impacts.

Start Date	End Date	Action	Reason	Days Impacted
1/8/2026	1/13/2026	Dropped existing light power/energy data	"E-72 Zone 1 operated at reduced power (~30%) for approximately five days. The site operator performed manual resets. The symptoms were consistent with an intermittent fault in the vendor supplied timer/contactor (the same component that later failed on 2026-03-11)" per the documentation provided by the lighting installers.	5
2/2/2026	2/5/2026	Dropped new light power/energy data	New lights initial installation day and breaker trip followed by make-up lighting	3
2/9/2026	2/14/2026	Dropped new light power/energy data	New lights additional breaker trip and atypical lighting operation	5
2/21/2026	2/26/2026	Dropped new light power/energy data	New lights additional breaker trip and atypical lighting operation. "short-circuit condition in the DC daisy-chain wiring" per the documentation provided by the lighting installers.	5

Note: Representations of the raw data—e.g., time series of raw power data—include the dropped data above. The team dropped the dates above in summary plots and tables.

The team created visualizations to review the raw data for any significant outliers, and the data were found to fall within reasonable bounds.

Data Analysis

The following formulas were used to calculate energy and demand savings.

- Energy savings (kWh):

$$Energy\ Savings\ (kWh) = \ (Baseline\ Power\ (kW) - Post\ Intervention\ Power\ (kW))$$

- Demand savings (kW):

$$Demand\ Savings\ (kW) = Basline\ Power\ (kW\ Peak) - Post\ Intervention\ Power\ (kW\ peak)$$

Peak demand was calculated according to the Design Energy Efficiency Rating method for calculating peak demand reductions, which uses an estimated average grid level impact for a measure between 4:00 p.m. and 9:00 p.m. during a "heat wave." It was defined after the fact by identifying the three consecutive weekdays with the hottest weather conditions that are expected to produce a regional grid peak event; peak days for Climate Zone 10 are June 26 through July 1. However, it is important to note that the study window occurred during the winter months, which did not overlap with the identified peak window. As a result, the peak demand reductions calculated in this study are based on modeled assumptions rather than direct measurements during peak demand days. This limitation should be considered when interpreting the demand savings results, as they may not fully reflect real-world peak conditions.

In real-world greenhouse operations, demand impacts can vary significantly depending on the crop type and DLI target. For example, certain crops—such as petunias, snapdragons, dianthus, and poinsettias—do not require supplemental lighting at all during non-winter months. In contrast, crops like cannabis and tomatoes often require DLI-controlled supplemental lighting year-round, including during summer months. This variability means that the demand impact of greenhouse lighting controls depends heavily on the specific crop being grown and its lighting requirements.

We attempted to normalize savings for operational changes such as crop mix or production shifts, but there were prolonged periods where the intervention greenhouse was not operational, which prevented a normalized comparison. Based on the definition of the peak demand period not overlapping with the nighttime interruption light operation, the study did not find peak demand or TOU savings. However, future projects can use the nighttime interruption load shape measured in this study to inform California Energy Data and Reporting System for cost-effectiveness calculations across greenhouses with different crop types.

Findings

Overview of Key Findings

This section provides a summary of the key findings from the field demonstration, organized by research questions. The findings highlight the challenges encountered during the implementation of DLI-based lighting controls, the insights gained from the data collected, and the implications for future research and program design. The structure of the remainder of this section includes detailed results, data analysis, stakeholder feedback, and recommendations.

Research Question 1

How do DLI-based lighting controls affect total lighting energy consumption and peak demand compared to conventional lighting operation?

- **Finding 1.1**: The DLI controls were not tested due to commissioning and operational challenges. As a result, energy savings and peak demand impacts could not be evaluated under DLI-driven operation.
- **Finding 1.2**: Baseline data provided valuable insights for Title 24 code enhancement models, which currently assume year-round lighting use. The study revealed that peak demand savings were crop-dependent, and certain crops (e.g., poinsettias, petunias, snapdragons, dianthus)

only required supplemental lighting during winter months. This contrasts with Title 24 models, which rely heavily on cannabis data and assume constant lighting use throughout the year. This affects calculated cost effectiveness for these types of sites.

- **Finding 1.3**: The inability to commission the DLI controls based on solar input meant that lighting schedules were manually set during the five-day window when the site considered the lights "fully commissioned" to achieve energy savings. Outside that window, commissioning and operations challenges resulted in over-lighting during some periods and increased energy use compared to the baseline.
- **Finding 1.4**: The change from daylight extension to nighttime interruption prevented demand savings during peak grid capacity periods. Certain crops did not require supplemental lighting during peak summer periods, limiting demand reduction potential.

Research Question 2

To what extent can precision light management improve crop productivity and quality?

- **Finding 2.1:** Crop productivity and quality impacts were inconclusive due to the lack of DLI control implementation, uncontrolled production variables between the intervention and baseline greenhouses, and the short duration of the "fully commissioned" intervention period (only five nights).

Research Question 3

What operational, behavioral, or environmental factors influence the performance and adoption of DLI-based greenhouse lighting systems?

- **Finding 3.1:** Operational and commissioning challenges led the growers, who reverted to manual timer adjustments. Proper commissioning and light sensor-based control are critical for successful implementation of DLI-based lighting systems.
- **Finding 3.2:** Multiple factors likely contributed to the control challenges observed, but the relative contribution of each cannot be fully determined from this demonstration. In particular, it remains unclear whether the issues were primarily due to installation/commissioning, the behavior of the driver and control logic under a nighttime interruption scheme, the PPFD sensor's performance at low-light levels, or other site-specific factors. Further investigation—such as controlled testing of the driver and sensor under both nighttime interruption and daylight extension operation, along with a review of vendor documentation—is needed to confirm whether this and similar DLI lighting controls can reliably dim autonomously, as well as to understand the implications of nighttime interruption versus daylight extension for system performance and crop risk. Growers and vendors may also be reluctant to implement aggressive dimming or major changes to lighting schedules without prior experience with either nighttime interruption or daylight extension due to the potential risk to crop health and yield. This operational conservatism can limit the extent to which DLI-based autonomous dimming is tested in real-world demonstrations.
- **Finding 3.3**: The external PPFD sensor was not calibrated for low-light levels encountered during nighttime interruption, which may have contributed to the vendor control system's inability to function as intended.

Detailed Results

Baseline Measurements and Load Characterization

During the baseline observation period, lighting was not regularly operated in either greenhouse due to shipping delays and operational changes. To capture a snapshot of lighting power demand, the research team requested that site operators manually turn on the lights in the baseline greenhouse (E-72) for a 17-minute period. The average lighting power during this period was 5.14 kW, accounting for nearly 60 percent of the total electrical load. Non-lighting loads (e.g., fans, pumps, and controls) were estimated by dividing the total measured load by two, assuming non-lighting loads were approximately evenly distributed between the two greenhouses at the time of the spot check. This simplifying assumption was necessary because lighting and non-lighting circuits were not metered separately, and only one greenhouse's lights were manually turned on during the 17-minute measurement. However, operational differences between the greenhouses during the implementation period (e.g., one house being fully planted while the other was not) suggest this equal-distribution assumption may have understated the non-lighting load for the baseline greenhouse.

In an ideal scenario, baseline characterization would include separate metering of lighting and non-lighting circuits in each greenhouse and/or a longer monitoring period under representative operating conditions in both houses. Given the installation delays and operational changes at this site, the 17-minute spot measurement should be interpreted as a rough indication of the lighting's contribution to the total load rather than a precise estimate of non-lighting consumption. This brief measurement highlights the significant contribution of supplemental lighting to total greenhouse energy consumption, underscoring its potential as a target for energy efficiency and load-shifting strategies.

Intervention Lighting System Performance

The intended design for the intervention lighting system was to dynamically adjust lighting levels based on natural sunlight using a daylight extension DLI management strategy. However, the site used nighttime interruption seasonal supplemental lighting for the crops grown in these greenhouses. Changing the intervention lighting to provide nighttime interruption lighting led to many commissioning challenges. Along with delaying commissioning and greatly compressing the duration of usable data, it also ultimately prevented verification of any autonomous DLI control functionality.

The site master grower manually set a fixed timer schedule irrespective of solar input, similar to the control greenhouse. Over the entire course of the concurrent lighting period, the intervention lights consumed more power than the existing lights, as shown in Figure 8. While the intervention fixtures were equipped with dimming capabilities, dimming was observed only through manual intervention during the study, limiting the system's ability to respond to natural sunlight levels. The intervention lighting never dimmed autonomously. Therefore, the intervention lights never showed a reduction power consumption and remained a greater consumer of power than the existing lighting.

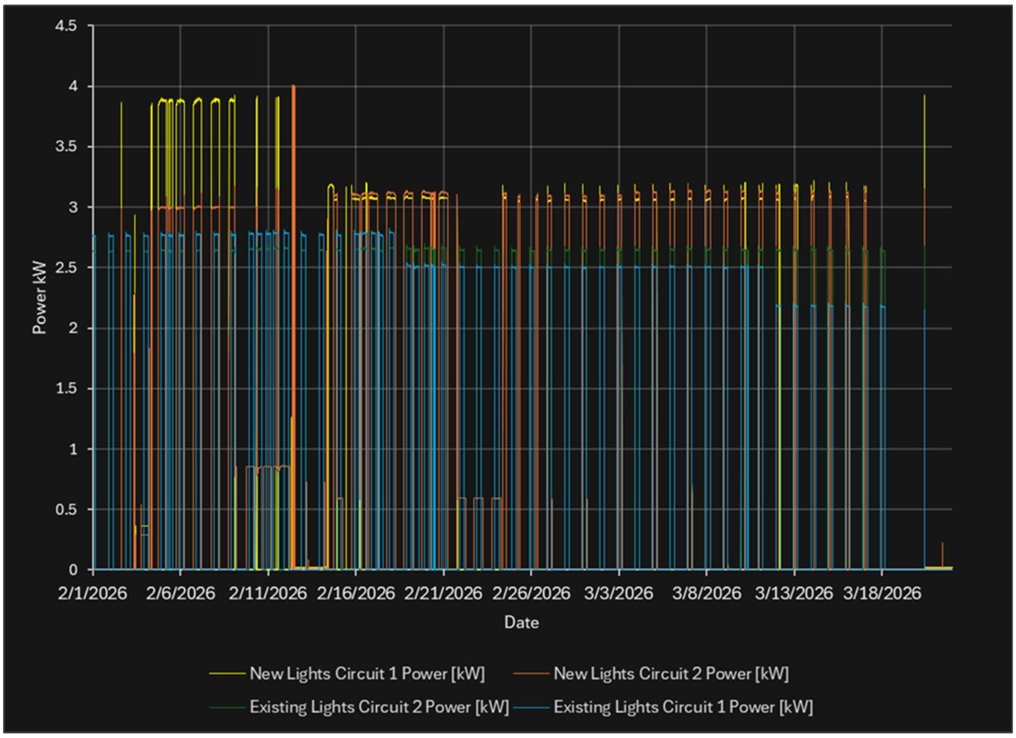

Figure 8: Lighting power over concurrent lighting period.

Strictly due to a reduced duration of lighting, the intervention lights did show some energy savings in the "fully commissioned" period. During the "fully commissioned" period, which spanned five nights from March 12 to March 17, 2026, the intervention lights demonstrated reduced energy consumption compared to the baseline lights. This reduction was solely due to shorter nighttime lighting durations and is not the result of true DLI-based control. Table 3 summarizes the lighting time statistics during this period, showing that the intervention lights operated for an average of 3.56 hours per night, compared to 6.38 hours for the baseline lights.

Table 3: "Fully commissioned" period (March 12–16) lighting statistics.

Metric	Units	Value
Duration Days	Days	5
Existing Lights Total Energy	kWh	154.3
New Lights Total Energy	kWh	114.5
Existing Lights Average Daily Energy	kWh/day	25.7
New Lights Average Daily Energy	kWh/day	19.1

Metric	Units	Value
Daily Lighting Energy Impacts	kWh/day	6.6
Daily Lighting Energy Impacts	%	26%
Existing Lighting Average Nighttime Duration Per Day	Hours/day	6.38
New Lighting Average Nighttime Duration Per Day	Hours/day	3.56

Figure 9 depicts the daily energy use of the intervention and baseline lighting systems during the "fully commissioned" period, which show that the duration of supplemental lighting decreases when natural solar input decreases, which is the opposite of the intended DLI control. In addition, this figure highlights the compressed nature of the "fully commissioned" period and its limitations in evaluating the system's performance. Again, the "fully commissioned" period spanned only five days and therefore could not represent DLI changes seasonally nor could the effects on plant quality and yield be evaluated.

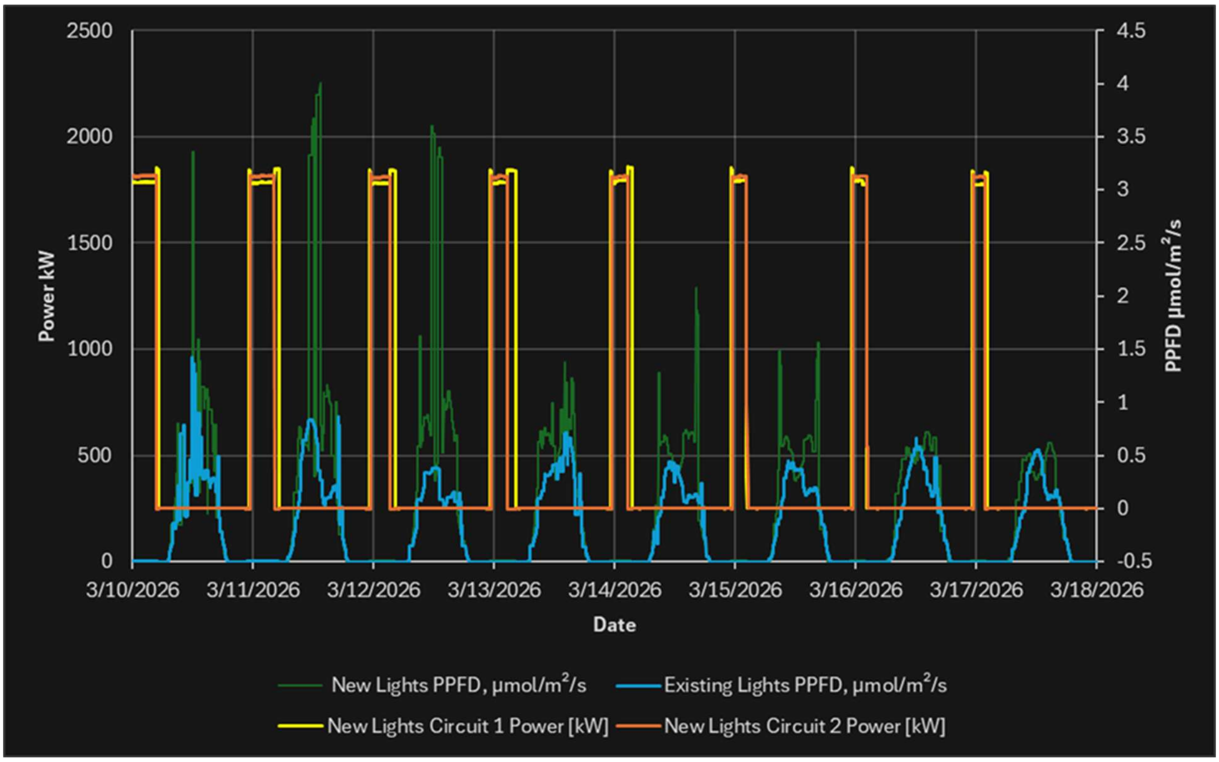

Figure 9: Lighting power and PPFD during "fully commissioned" period.

Analysis found that throughout the entire concurrent lighting period, there was a substantial difference in PPFD per watt between the baseline and intervention lighting systems. Figure 10 shows that the PPFD per watt delivered by the intervention lighting was significantly greater than the existing lighting. Over the course of the concurrent lighting period, the new lighting provided 162 percent of the PPFD per watt compared to the baseline existing lighting.

This was an unexpected finding, given that the specifications of the baseline lights claimed 2.1 micromoles per joule and the intervention lighting claimed 2.5 micromoles per joule for the same 50 watts of power. Additional analyses of the lighting levels, sensor calibration, age of existing lighting system, and environmental conditions are required to fully understand the factors contributing to this discrepancy. It is possible that variations in sensor placement, measurement methodology, or operational conditions may have influenced the observed results. A future study in a controlled research setting could evaluate this difference by measuring power consumption and light intensity across several points for each of the light fixtures.

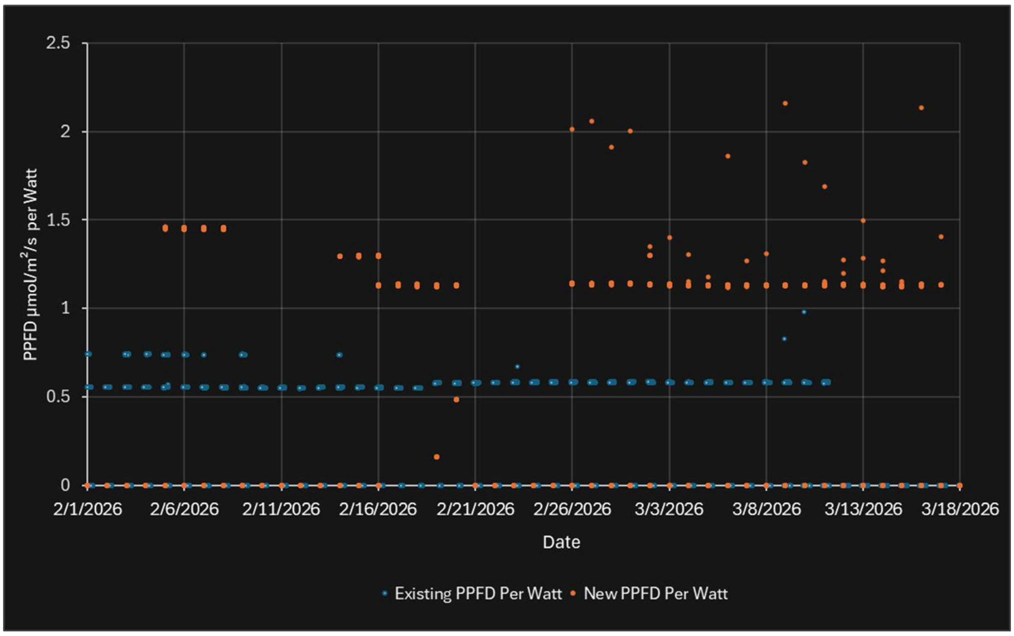

Figure 10: PPFD per watt of existing and new lighting during concurrent lighting period.

Operational Challenges and Deviations

The field demonstration faced several operational and commissioning challenges that significantly impacted the implementation and performance of the DLI-based lighting controls. These challenges not only limited the system's ability to operate as intended, but also introduced complexities in data interpretation and cross-greenhouse comparisons. The following timeline outlines the key events and insights with additional context to address the broader challenges encountered during the study.

PHASE 1: INSTALLATION (SEPTEMBER 2025–FEBRUARY 2026)

The installation phase was delayed due to shipping logistical delays and subsequent larger delays caused by waiting for a gap in active crop cycles so that intervention lights could be installed. These compounding delays severely compressed the timeline for subsequent phases.

- **September 29, 2025:** E-70 fixtures were delivered to the site. However, installation was deferred because the intervention greenhouse was in active poinsettia production.

- **Late November 2025:** Following the poinsettia harvest, the team hung the fixtures in the intervention greenhouse. However, direct current (DC) cabling and controller integration were still in progress.
- **December 8, 2025:** Metering equipment first detected power activity in the baseline greenhouse (E-72) under its normal winter schedule.
- **December 30, 2025:** The site confirmed that controller hardware and DC cabling work for the intervention greenhouse remained incomplete.
- **February 3, 2026:** The new lights were used for the first time in the intervention greenhouse (E-70).

The installation timeline was constrained by the site's commercial crop schedule, which delayed the deployment of the intervention system. Future projects should allocate a pre-installation buffer of at least four months to account for crop cycles' impact on installation, particularly during busy seasons.

PHASE 2: COMMISSIONING (JANUARY 2026–MARCH 11, 2026)

The vendor lighting system commissioning phase encountered multiple setbacks, including vendor sensor misplacement, circuit protection issues, and extended downtime for the intervention system. These challenges delayed the activation of adaptive DLI controls and limited the system's ability to operate as intended.

- **January 8–13, 2026:** The baseline greenhouse (E-72) experienced reduced power (~30 percent) for five days due to an intermittent timer/contactor fault. The site operator performed manual resets.
- **January 16, 2026:** E-72 was formally placed on its experimental schedule of 10:00 p.m.–4:00 a.m. at full intensity. This differed from the originally planned 9:00 p.m.–3:00 a.m. schedule.
- **Mid-January 2026:** We relocated an independent PPFD validation sensor, initially installed in the wrong greenhouse, to the intervention greenhouse (E-70).
- **January 22–23, 2026**: The team installed a controller-specific PAR feedback sensor in E-70. Adaptive control could not operate before this date, and the system ran as fixed output.
- **February 4–5, 2026:** E-70 ran for 12 hours (5:00 p.m.–5:00 a.m.) to recover photon accumulation lost during earlier downtime. A second extended run occurred on February 5, lasting approximately 16 hours.
- **February 9–14, 2026:** Circuit protection for E-70 tripped due to an overload condition. The system was partially operational for five days while the fault was diagnosed and the breaker configuration adjusted.
- **February 21–26, 2026:** A short-circuit condition in the DC daisy-chain wiring caused the intervention system to run in a degraded state for several days. Repairs were completed on February 26, and the nominal schedule was adjusted to 10:00 p.m.–4:00 a.m. to align with E-72 and reduce circuit stress.
- **March 11, 2026:** E-72 Zone 1 experienced a partial component failure, reducing its daily energy use from 15.7 kWh to 13.7 kWh. Zone 2 continued operating normally.

The site master grower's decision to implement nighttime interruption instead of daylight extension further limited the system's ability to achieve demand savings during peak grid capacity periods. Nighttime interruption required the lights to operate at full power during the night, whereas daylight extension would have allowed for dimming during periods of natural sunlight. Additionally, the PPFD sensors were selected for the planned daylight extension operation, so they were not calibrated for low-light levels encountered during nighttime interruption, reducing its reliability and potentially contributing to the system's failure to dim autonomously.

In future studies, commissioning should be defined as the point at which the full control loop, including the controller and feedback sensors, is verified to be controlling the lights operation based on solar input. Using this definition, the system tested was never truly commissioned, as the intervention greenhouse ultimately reverted to using manual timing controls irrespective of solar input. The challenges the site faced with system integration led to the use of manual timing controls (irrespective of the sunlight received during the previous day), so there was no adaptive control performance to evaluate. Additionally, future studies should investigate the energy savings potential of daylight extension that is likely to offer greater energy savings and fewer implementation challenges.

PHASE 3: OPERATION (MARCH 12–MARCH 16, 2026)

The operational phase was significantly compressed due to delays in the earlier phases, resulting in a limited control window of only five days. However, due to commissioning challenges, dynamic control of lighting duration, intensity, or spectrum was never achieved in the intervention greenhouse. The intervention greenhouse reverted to manual timer-based controls at full intensity, irrespective of sunlight received the previous day.

- **March 12–16, 2026**: Due to commissioning challenges, the site operations managers overrode the adaptive DLI mode in the intervention greenhouse and set a manual timing schedule. The operator adjusted its shutoff time progressively earlier each night; however, the accumulated daytime PAR had decreased each day, which should have resulted in later shut off times, if the lights were based on sunlight received the previous day. By the final night, the intervention lights operated for only 2.35 hours, consuming 12.86 kWh, compared to 6.48 hours and 30.79 kWh for the baseline. This was due to manual timing adjustments, which were not related to the amount of PPFD the plants received during the day, as shown in Figure 9.
- **March 17, 2026**: The site terminated supplemental lighting for the season, consistent with its typical December through April supplemental lighting window. Both greenhouses ceased operation by March 18 as the winter/early spring growing cycle concluded and natural daylight became sufficient. The installed LED systems remain in place and are expected to be used in subsequent supplemental lighting seasons, with the grower indicating interest in further experimentation with the control strategy.

Differences in plant counts and schedules between the greenhouses further complicated comparisons. The baseline greenhouse (E-72) produced a total of 60,427 plants, while the intervention greenhouse (E-70) produced only 18,691 plants; specific plant counts and crop cohort weighted average cycle times are reported in Table 4. The large disparity in production likely affected environmental conditions, such as humidity and CO_2 levels. Regarding crop impacts, neither greenhouse reported any waste, but the intervention period was such a small portion of the plant growth cycle that no conclusion could be attributed to the control of the lights. These differences introduced variability that made it difficult to isolate the effects of the lighting intervention on environmental conditions or crop impacts.

The actual intervention window was significantly shorter than planned and no daylight adaptive control of the lighting occurred, limiting the ability to evaluate the system's performance or crop impacts under DLI-based controls.

Table 4: Plant production by greenhouse.

Pot Date	E-72 Plant Count	E-72 Cycle Time	E-70 Plant Count	E-70 Cycle Time
Dec 8, 2025	4,192	10.4 weeks	-	-
Dec 15, 2025	7,917	9.8 weeks	-	-
Dec 22, 2025	1,551	9.2 weeks	-	-
Dec 29, 2025	4,308	9.0 weeks	-	-
Jan 12, 2026	1,796	11.3 weeks	-	-
Jan 19, 2026	3,774	7.0 weeks	-	-
Jan 26, 2026	6,725	9.1 weeks	346	13.0 weeks
Feb 2, 2026	16,039	9.4 weeks	2,699	9.0 weeks
Feb 9, 2026	9,710	8.5 weeks	5,156	8.4 weeks
Feb 16, 2026	2,160	7.9 weeks	8,465	10.9 weeks
Mar 30, 2026	2,255	6.0 weeks	2,025	7.0 weeks
TOTAL/AVG	60,427	Avg 8.98 weeks	18,691	Avg 9.27 weeks

PHASE 4: WRAP-UP AND DATA RECONCILIATION (APRIL–MAY 2026)

The final phase of the project focused on reconciling the event log with the metered data and preparing the draft report.

- **April 10, 2026:** The EM&V contractor team transmitted the full dataset, containing 176,402 minute-resolution power records.
- **April 13–17, 2026:** The site operator provided a confirmed event log and production data covering the full study period.
- **May 29, 2026:** The EM&V contractor team completed the analysis.

Accurate and timely documentation of operational events is critical for reconciling discrepancies between the event log and metered data. Future studies should implement change-notification protocols with site rewards or penalties to ensure that any operator-driven schedule adjustments are captured sooner.

The operational challenges and deviations encountered during this field demonstration underscore the complexities of implementing DLI-based lighting controls in commercial greenhouse environments. Delays in installation and commissioning, coupled with equipment failures and operational deviations, significantly compressed the intervention window and limited the ability to evaluate system performance. These challenges highlight the importance of site selection, site buy-in, planning with large schedule buffers, thorough commissioning, and effective communication between all stakeholders to ensure the success of future deployments.

Energy and Demand Impacts

This section presents the energy and demand impacts observed during the study. The team evaluated energy and demand impacts based on interval-metered electricity data. However, the inability to commission the DLI controls limited the ability to assess true savings or peak demand impacts. Verified energy savings were based on manual programmable schedules irrespective of solar input rather than dynamic DLI-driven operation.

The intervention lights consumed more energy than the baseline lights during the majority of the metering period, due to providing more lighting than the existing lights. During the five-day operational period, the intervention lights were able to use 26 percent less energy due to shorter run times, as shown in Table 3; however, those run times were set manually by the site operators rather than adjusted based on the sunlight received. Additionally, the intensity of the intervention lights never dimmed as seen in the constant power draw in both intervention and baseline lights (Figure 11).

We found that the potential for peak demand savings was crop-dependent, with low DLI target crops—such as poinsettias and petunias—requiring supplemental lighting only during winter months. This contrasts with Title 24 models, which assume year-round lighting use based on cannabis and vine crop data. The TOU rate analysis was not applicable due to the fixed nighttime interruption schedules outside the summer peak demand window and lack of DLI control implementation, and nighttime interruption does not apply to analyzing TOU rate impacts since its operations are outside the daily TOU on peak hours. Because the vendor never established DLI control, we cannot extrapolate beyond the time of year we observed to model how reduced supplemental lighting during summer usage would impact peak grid demand.

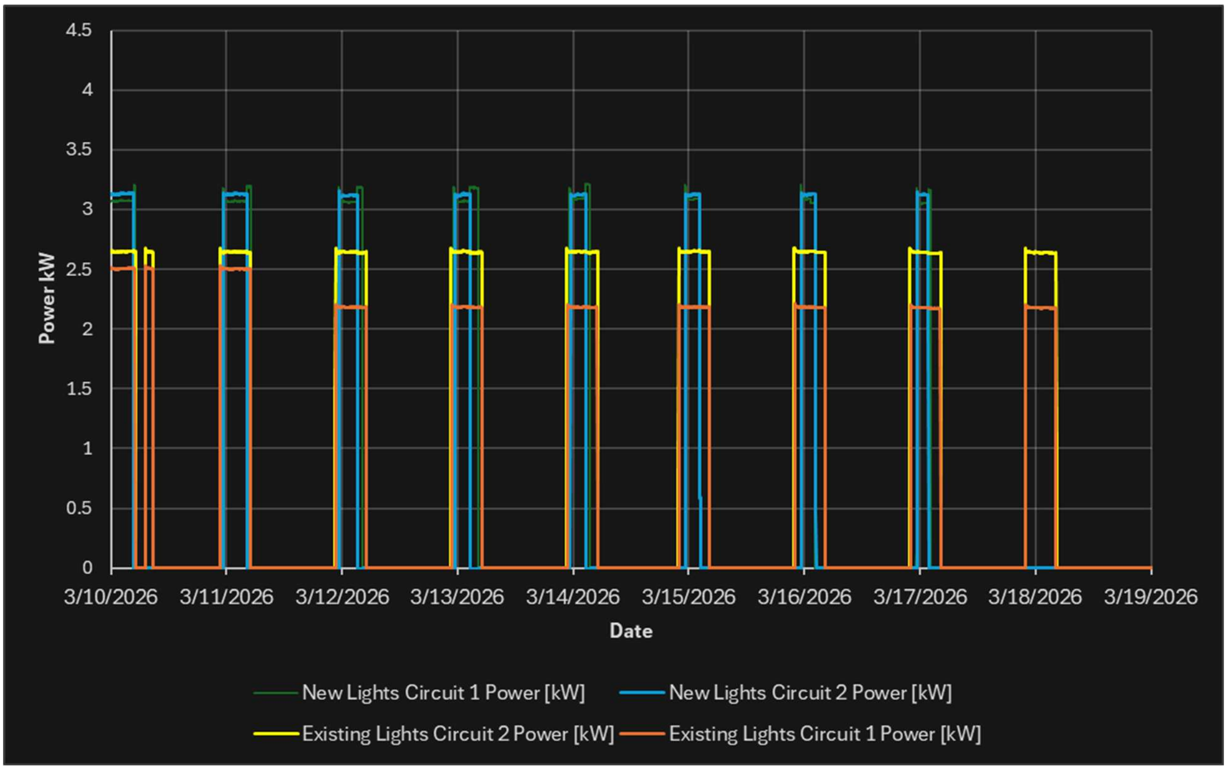

Figure 11: Lighting power during "fully commissioned" period.

Environmental Sensor Results

It is important to note that none of the environmental sensor findings in this section are directly relevant to DLI-based lighting controls, as the lights were not controlled using DLI strategies during the study. The intervention greenhouse relied on fixed, timer-based controls due to commissioning challenges, and there were numerous site operations' decisions that led to independent production variables that were not controlled for between the two greenhouses. Additionally, the lights were only considered "fully commissioned" for a brief five-day window, which still did not represent true DLI functionality. This window is too short relative to the full crop growth cycle to draw conclusions about the impact of lighting on environmental conditions or crop outcomes.

Throughout the study, the team monitored environmental conditions to assess differences between the two greenhouses due to site operations. Greenhouse E-70 (intervention) was observed to be slightly warmer and drier than greenhouse E-72 (baseline), which was likely influenced by disparities in plant counts and shading practices. For example, the intervention greenhouse produced only 18,691 plants compared to the baseline greenhouse, which produced 60,427 plants. The differences in plant production would have impacted humidity levels due to differences in transpiration rates. Additionally, shading was deployed in E-70 to protect the remaining plants, while no shading was used in E-72, further contributing to the environmental variability.

The CO_2 levels also varied significantly between the two greenhouses, with higher levels observed in E-70. This discrepancy was likely due to the use of a ventless heater in the intervention greenhouse, which released combustion gases directly into the space. The lack of a visible flue or heat exchanger, combined with elevated CO_2 levels, supports this conclusion. Other factors—such as heater location, potential exhaust leaks, and prevailing wind direction—may have also contributed to the observed variability.

While these observations provide useful context for understanding the environmental conditions in each greenhouse, they underscore the limitations imposed by site operations deviating from the plan. The lack of control over key variables, combined with the short duration of the "fully commissioned" period, prevents any definitive conclusions from being drawn about the relationship between lighting control, environmental conditions, and crop outcomes.

The environmental sensor data collected during this study highlights the complexities of evaluating greenhouse lighting systems in real-world conditions. The uncontrolled variables between the two greenhouses, combined with the absence of true DLI-based lighting control, limit the applicability of these findings to DLI strategies. Future studies should select only sites that can commit to following the study plan and control environmental variables more rigorously and ensure that lighting systems are fully commissioned and operating as intended for a sufficient duration to capture meaningful data.

Analysis

The study did not achieve the objective of evaluating DLI-based lighting controls due to commissioning and operational challenges. However, the challenges encountered during this field demonstration provided valuable insights into the complexities of implementing DLI-based lighting controls in commercial greenhouse environments. These lessons highlight the importance of robust planning, proper commissioning, and effective communication to ensure the success of future deployments. The key lessons learned—summarized below and in a subsequent section—provide actionable recommendations derived from the study.

1. **Proper Commissioning**
   The inability to fully commission the DLI controls was a major barrier to achieving the intended energy savings and crop performance outcomes. The intervention greenhouse ultimately reverted to manual timer-based controls, which prevented the evaluation of true DLI-driven operation. This underscores the need for robust commissioning protocols that verify the full control loop, including the controller, feedback sensors, and integration with environmental inputs.
2. **Grower Resistance to Complexity**
   Resistance from growers to adopt complex systems that were not performing as expected was a recurring challenge. The failure of the automated system to perform as intended led growers to revert to manual timing adjustments. This highlights the need for user-friendly designs and comprehensive training to build grower confidence and mitigate reliance on manual controls.
3. **Variability in Crop Lighting Needs**
   The study revealed significant variability in lighting needs across different crops. For example, poinsettias, petunias, and other low-DLI crops require supplemental lighting only during winter months, whereas cannabis and tomatoes often require year-round lighting. This variability demonstrates the importance of tailoring program and code assumptions to specific crop types to avoid overburdening growers with unnecessary costs and requirements.

4. **Operational Deviations Complicate Comparisons**
   Operation deviations—e.g., reverting to manual timing controls—and production differences like plant counts, schedules, and environmental conditions between the greenhouses introduced variability that made it difficult to isolate the effects of the lighting intervention.
5. **Daylight Extension vs. Nighttime Interruption**
   The master grower's decision to implement nighttime interruption instead of daylight extension limited the system's ability to achieve demand savings during peak grid capacity periods. Daylight extension, which allows for dimming during periods of natural sunlight that coincide with peak demand periods, may offer greater demand savings and fewer implementation challenges compared to nighttime interruption.

Stakeholder Feedback

Stakeholder engagement is a key component of the broader technology transfer process for this project. Early coordination ensures that utilities, program implementers, and industry groups have opportunities to provide guidance, validate research priorities, and prepare for the eventual integration of findings into incentive programs or codes and standards activities. Although stakeholder engagement is ongoing, several interactions have informed the change in direction of the project.

The project team has engaged an early set of greenhouse industry and utility program stakeholders, including the Resource Innovation Institute, which represents a broad cross section of controlled environment agriculture practitioners; PG&E's California electrical Technical Reference Manual (eTRM) development staff; and staff from the PG&E AESAP. Additional discussions are planned with agricultural energy efficiency programs across California's IOUs with greenhouse focused offerings, as well as members of the California Codes and Standards Enhancement working groups and other controlled environment agriculture industry groups.

Initial stakeholder feedback was positive. Respondents expressed strong interest in the project's potential to provide empirical data on advanced DLI-driven lighting controls, which has been identified as a major gap for both utilities and growers. Stakeholders noted that credible field data would help inform measure development in the eTRM, refine assumptions used in program cost effectiveness tests, and make codes and standards enhancement decisions, as well as improve growers' confidence in adopting emerging control technologies. Utility program staff indicated that the project's use of IPMVP Option B adds rigor that will support future incentive design, while industry groups emphasized the value of understanding lighting's interaction with environmental conditions and crop outcomes.

Overall, stakeholder responses confirm that the project objectives align well with both industry needs and utility program priorities. The feedback underscores the importance of continuing coordination and pursuing more data and demonstrations that better align with the original project objective, and it signals that there will be strong interest in the findings presented in this report. The project also furthered data collection and implementation observations of true DLI-controlled intervention lighting to improve understanding and promote the adoption of these technologies.

This feedback process helps ensure that the findings and recommendations are aligned with stakeholder priorities and address any gaps or concerns. Efforts will also be made to publish a journal article summarizing the research and present it at an industry conference to further disseminate the findings, promote broader industry engagement, and provide a lasting resource for both technical and non-technical audiences. These steps are intended to maximize the impact of the study, facilitate knowledge transfer, and support the adoption of advanced DLI-driven lighting controls across the greenhouse industry.

Recommendations

1. **Prioritize robust commissioning.**
   Future deployments should define "commissioning complete" as the point at which the full control loop is verified and operational. This includes ensuring that the controller, feedback sensors, and dimming capabilities are functioning as intended based on solar input. Commissioning should be completed well in advance of the operational window to allow for troubleshooting and adjustments.
2. **Simplify system design and provide training.**
   Future DLI-based systems should be easier for growers to understand and operate. Controls and user interfaces should align with growers' existing supplemental lighting strategies (e.g., daylight extension and, where relevant, nighttime interruption) and clearly indicate how the system responds to light conditions. Targeted training and limited-scope trials within the grower's operation can help connect DLI concepts to crop outcomes and build confidence in the technology before full-scale adoption.
3. **Tailor programs and codes to crop-specific needs.**
   Utility programs and code enhancements should account for the variability in lighting needs across different crops. For example, Title 24 models, which currently assume year-round lighting use based primarily on cannabis data, should be updated to include exceptions for crops with seasonal lighting needs. This would improve cost-effectiveness and market adoption while ensuring equitable participation.
4. **Investigate daylight extension as an alternative.**
   Future studies should explore the energy savings potential of daylight extension compared to nighttime interruption. Daylight extension may allow for demand savings and may impact energy consumption. Additionally, if nighttime interruption was a contributing factor to the system's failure to dim autonomously, this should be considered in future implementation strategies.
5. **Control environmental variables.**
   Future studies should aim to control environmental variables more rigorously to isolate the effects of lighting interventions. This includes standardizing plant counts, schedules, and shading practices between greenhouses. Additionally, the use of ventless heaters, which contributed to elevated CO_2 levels in the intervention greenhouse, should be avoided or mitigated if possible.
6. **Implement change-notification protocols.**
   Accurate and timely documentation of operational events is critical for reconciling discrepancies between the event log and metered data. Future studies should implement change-notification protocols to ensure that any operator-driven schedule adjustments are captured in real time rather than reconstructed later from metered data and discussions with operators.

7. **Build redundancy into project timelines.**
   The compressed operational window in this study limited the ability to evaluate the system's performance under varying conditions. Future projects should explore crops with longer supplemental lighting seasons, as well as build redundancy into their timelines to account for delays in installation and commissioning.

The challenges faced in this study are emblematic of the broader difficulties in scaling emerging efficiency technologies—these types of challenges are not unique to DLI-based lighting systems but are common across many other technologies. Addressing these challenges through better implementation practices, stakeholder engagement, and program and code design will be critical to increasing market adoption and achieving long-term energy savings. By prioritizing robust commissioning, tailoring programs to crop-specific needs, and addressing operational complexities, future efforts can achieve greater energy savings and demand reduction to drive broader market adoption.

References

Elkins, C. A. (2020). *Evaluation of Different Lighting Strategies Used to Improve Efficiencies in Plant Growth for Controlled Environment Agriculture.* University of Georgia, College of Agricultural and Environmental Sciences, Department of Horticulture. Retrieved from https://openscholar.uga.edu/record/5742?v=pdf

Mattson, N. T. (2020). *Plant Responses to Integrated Light and CO_2 Control.* The Greenhouse Lighting and Systems Engineering (GLASE) Consortium. Retrieved from https://glase.org/wp-content/uploads/2020/03/Technical-Reportissue5.pdf

Mosharafian, S. S. (2020). Development and Implementation of a New Optimal Supplemental Lighting Control Strategy in Greenhouses. *Proceedings of the ASME 2020 Dynamic Systems and Control Conference (DSCC2020)* (pp. Paper No. DSCC2020-24540). Pittsburgh, PA: American Society of Mechanical Engineers. Retrieved from https://www.researchgate.net/profile/Shirin-Afzali-2/publication/348800824_Development_and_Implementation_of_a_New_Optimal_Supplemental_Lighting_Control_Strategy_in_Greenhouses/links/6035da94299bf1cc26e7f02c/Development-and-Implementation-of-a-New-Optima

Rengasamy, N. R. (2022). Artificial Lighting Photoperiod Manipulation Approach to Improve Productivity and Energy Use Efficacies of Plant Factory Cultivated Stevia rebaudiana. *Agronomy*(12), 1787. Retrieved from https://doi.org/10.3390/agronomy12081787

Torres, A. P. (2025, December 15). *Measuring Daily Light Integral in a Greenhouse.* Retrieved from Purdue Extension, Department of Horticulture and Landscape Architecture, Purdue University: https://flowers.hort.purdue.edu

van Iersel, M. W. (2016). An Adaptive Control Approach for Light-emitting Diode Lights Can Reduce the Energy Costs of Supplemental Lighting in Greenhouses. *HortScience*(52), 72-77. Retrieved from https://doi.org/10.21273/HORTSCI11385-16

Zhang, M. J. (2025). The Impact of Daily Light Integral from Artificial Lighting on Tomato Seedling Cultivation in Plant Factory. *Agronomy*(15), 1:70. Retrieved from https://doi.org/10.3390/agronomy15010070