Smart Controls for Data-Driven Indoor Agriculture Field Evaluation

Final Report

ET23SWE0067

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Executive Summary

The CalNEXT ET23SWE0067 Smart Controls for Data-Driven Indoor Agriculture Field Evaluation project, conducted from 2023 to 2025, explored the market potential for and evaluated the impact of “smart controls” technologies on controlled environment agriculture (CEA). This method of agriculture involves the cultivation and manufacturing of floriculture, food, and cannabis products. The study focused on automated, integrated, and intelligent environmental controls technologies used in indoor and greenhouse CEA facilities in California. Smart controls monitor, evaluate, and control energy consumption of the facility’s heating, ventilation, and air conditioning; lighting; crop irrigation; and nutrient management systems.

The project investigated smart CEA controls, which must be capable of one or more of the following functions:

- **Automation:** Hardware and software that optimize individual CEA systems, reducing labor—as well as electricity use and demand—by implementing control strategies for lighting, HVAC, and irrigation systems. These strategies include scheduling, dimming, daylighting, temperature and humidity optimization, staging and modulation of pumps and fans, and demand management.
- **Integration:** Hardware and software that optimize and connect CEA systems—including lighting, heating, ventilation, cooling, as well as irrigation and fertigation—to electricity use and demand.
- **Artificial intelligence:** Hardware and software systems that use machine learning, cameras and sensing technology to optimize resources like water and fertilizer, as well as electricity use and demand, based on plant growth and quality characteristics. These characteristics include light levels, temperature, humidity, airflow, and irrigation flowrates, among others.

The project included a market assessment, field evaluations, and this technology roadmap to identify cost-effective energy efficiency and demand response measures for smart environmental controls in California’s CEA sector. The technology roadmap shares five program pathway recommendations, including ideas for two new energy efficiency measure packages:

1. Develop a deemed measure package for greenhouse supplemental lighting Daily Light Integral controls. Investor-owned utilities may have only three years to implement an energy efficiency program for Daily Light Integral controls before the energy code requires this automation strategy.
2. Develop a deemed measure package for greenhouse ventilation fan variable frequency drive controls. The existing agricultural fan measure is not applicable to greenhouses.

The following sections of this Executive Summary provide introductory smart controls definitions and highlighted findings from the various phases of the study. Refer to the Objectives section of this report to understand the methodology and stakeholder engagement results for each mechanism.

Market Assessment Highlights

During the market assessment phase of the project, literature review, surveys, interviews, and site visits supported a characterization of smart CEA controls adoption, technology penetration, and energy savings potential. Table 1 defines the five categories of control technology in California's 2025 controlled environment agriculture market, and the CEA Controls and Automation section of this report provides additional detail.

Highlights from the market assessment stakeholder engagement mechanisms are below.

Literature Review

The team conducted a literature review in 2023, which assessed more than 100 academic studies, trade journal articles, industry publications, and conference proceedings. Refer to the Introduction and Background sections of this report to understand the ways CEA operations use electricity, types of existing CEA controls technologies, currently available off-the-shelf technology, the latest vendor offerings in the market, and insights on controls decision-making logic. These sections also provide information on the energy savings potential of various controls strategies for lighting; heating, ventilation, and air conditioning; and irrigation systems.

Findings included demographics of indoor and greenhouse growers in California, which can help the investor-owned utility energy efficiency programs understand the controlled environment agriculture market to gain insights on energy efficiency opportunities in this sector.

- California had 4,611 greenhouses and indoor farms comprising 7,185 acres—or 313 million square feet—in 2022. This represents an 87 percent increase since 2017, mostly reflecting growth in the greenhouse industry.
- 61 percent of every square foot of a CEA facility in California is used for greenhouse floriculture or nursery crop production.
- Nine controls strategies identified in this review can reduce lighting; heating, ventilation, and air conditioning; and irrigation systems electricity consumption by up to 69 percent in California greenhouses and indoor farms.

Surveys

Growers across the state of California shared information in 2024 about their baseline control systems and level of automation, integration, and intelligence. Refer to the Survey Results section of this report for data visualizations of survey responses to understand the California CEA market's adoption of smart controlled environment agriculture environmental controls and barriers to energy efficiency; more detail is available in Appendix B. The average facility size represented by survey respondents is 259,000 square feet, and the median facility size represented in survey responses is 65,520 square feet.

CEA CONTROLS ADOPTION

- Large CEA farms--greater than 100,000 square feet—that grow food are more likely to employ smart environmental controls than small CEA facilities, or CEA farms that cultivate cannabis or floriculture crops.
- Respondents employing smart environmental controls were the only growers monitoring energy use at the system level.

BARRIERS TO ENERGY EFFICIENCY

- When surveyed about energy efficiency projects, 40 percent of survey respondents were primarily concerned with system performance, while 30 percent were concerned with associated capital cost.
- A majority of respondents—87.5 percent—wanted simple payback periods shorter than five years, while 37.5 percent of respondents preferred paybacks of less than two years.

Interviews

Industry experts and stakeholders across nine key CEA market segments provided feedback in 2024 and 2025. The Interview Findings section of this report illustrates the level of smart environmental controls adoption across food, floriculture, and cannabis cultivators in California; it also includes additional insights on the energy savings potential of smart environmental controls, as well as industry perspectives about baselines, industry standard practice, and the status of standards, energy codes, and third-party certification programs affecting CEA facilities.

SMART CONTROLS ADOPTION

- Energy code requirements for smart CEA controls are not in the final proposed measures for the 2025 code cycle, but there may be requirements introduced for the 2028 cycle.
- A third-party certification organization may create a qualified product library for networked horticultural lighting controls that could soon be available for California investor-owned utilities, which incentive programs will be able to reference.
- California cannabis, tomato, vegetable, herb, and strawberry growers are more likely to use smart heating, ventilation, and air conditioning controls than some floriculture growers due to higher profit margins and tighter plant-specific environmental requirements.
- The level of irrigation controls sophistication is heavily influenced by crop type.

Site Visits

The project team visited four CEA operations in four California climate zones to observe controls systems in the field and assess energy monitoring capabilities. Refer to the Site Visit Results section of this report to understand the level of smart controls adoption in each greenhouse and indoor farm. Appendix C includes system-level information for each site, with the average facility size represented at 1,224,950 square feet, and the median size at 43,900 square feet.

CEA CONTROLS

- The industry standard practice observed at site visits demonstrated higher levels of controls automation than surveys or interviews.
- 50 percent of the facilities the team visited used smart CEA controls for multiple systems.

Energy Analysis

Two data sets of electricity consumption history helped characterize the California CEA market in investor-owned utilities territory. The first data set uses monthly utility bill data from two greenhouses and one indoor farm in California to understand monthly electricity use, peak demand, and electric energy use intensity for a 12-month period. The second dataset uses a larger sample of CEA facilities using data shared by Pacific Gas & Electric to compare smaller, medium-sized, and larger growers. Refer to the Energy Analysis section of this report to review detailed information from the two data sets.

SITE-LEVEL ENERGY BENCHMARKING

- Indoor farm electric energy use intensity can be 29 times higher than greenhouse electric energy use intensity.
- Larger greenhouse growers consume more electricity in winter, likely because large greenhouses typically use artificial lighting seasonally for photoperiod extension. For this reason, large growers may present the greatest opportunity for energy savings from smart horticultural lighting controls.

Technology Roadmap Highlights

Using the recommendations from the market assessment, as well as the results of field demonstrations in three hard-to-reach communities in California, the Technology Roadmap identified and detailed low-cost, readily available solutions for adoption—especially those that would be successful in disadvantaged communities. The Recommendations section of this report provides an initial list of measures identified for further investigation in the field demonstrations phase of the project.

Field Demonstrations

The team installed smart controls systems in three greenhouses and one indoor farm in California to evaluate the energy savings potential of smart controls for CEA process systems and uncover a strategic direction for smart controls program development. These systems observed energy and environmental data for six months.

ENERGY SAVINGS POTENTIAL

- Automated greenhouse Daily Light Integral controls have the potential to achieve 53 to 78 percent electricity savings across leafy greens, tomato, and cannabis greenhouses in California's 16 CZ.
- Automated greenhouse ventilation fan variable frequency drive controls have the potential to achieve an average of 63 percent electricity savings across California's 16 CZ.

HARD-TO-REACH CUSTOMER INSIGHTS

- CEA businesses are more likely to be hard-to-reach customers because concentrations of cultivation facilities are in California counties that satisfy the geographic criteria. This means CEA businesses in hard-to-reach counties are hard-to-reach customers if they meet one of the other criteria—such as having leased buildings, being non-English speakers, or being a micro-business with less than 25 employees.
- Consider implementing rebate programs upstream with manufacturers and distributors to accelerate the adoption of smart CEA environmental controls.

Glossary of Terms

Controlled environment agriculture (CEA): Cultivation of crops under protection in spaces, including greenhouses and indoor farms. Referred to as controlled environment horticulture in California Title 24 energy code.

Controlled environment horticulture (CEH): Cultivation of crops under protection in spaces—including greenhouses and indoor farms—as defined by California Energy Code Title 24, Part 6 for CEH.

Decision tree: The simplest form of logic where data inputs are interpreted by if-then-else decision rules to predict output variables.

Energy use intensity: Expresses a building's energy use as a function of its size or other characteristics using units of kilo British thermal units per square foot per year.

Extended photosynthetically active radiation (ePAR): Photons from the 400 to 750 nanometers (nm) wavelengths.

Extended photosynthetic photon efficacy (ePPE): A measure of the energy efficiency of horticultural lighting systems that describes the amount of ePAR produced per unit of energy used measured in micromoles per joule (μmol/J).

Far red: Light spectrum from 700 to 800 nm, considered the extended PAR (ePAR) spectrum.

Feedback: Control loop that measures disturbances in the output of the controlled variable after they affect the system.

Feedforward: Control loop that measures disturbances before they affect the system.

Fertigation: The practice of applying fertilizer solutions with irrigation water.

Fuzzy logic: A methodology for variable processing that accommodates multiple possible truth values within the same variable.

Intercanopy lighting: Equipment delivering light to plants at lower elevations of plant canopy.

Model predictive control: An optimizing logic model that minimizes a cost function for a constrained system over a finite time horizon.

Neural networks: A type of machine learning model inspired by the structure and function of the human brain that learns to recognize patterns and relationships in an example dataset and adjust the weights of each connection to reflect them.

Photoacclimation: A lighting control strategy where light intensity is gradually increased as plants grow week by week.

Photosynthetically active radiation: Photons from the 400 to 700 nm wavelengths.

Photosynthetic photon efficacy: A measure of the efficiency of horticultural lighting systems that describes the amount of photosynthetically active radiation produced per unit of energy used in units of μmol/J.

Photosynthetic photon flux: A measure of the amount of photosynthetically active radiation photons hit a surface, like a plant canopy, with each second in units of μmol per square meter per second.

Policy gradients: Helps reinforcement learning programs maximize expected rewards by following a policy.

Proportional-integral-derivative: A control loop mechanism employing feedback.

Q-learning: A popular off-policy reinforcement learning algorithm that uses an action value function—the Q-function—to learn an optimal policy and update the algorithm iteratively.

Reinforcement learning: A type of machine learning focused on decision-making and control through a feedback-based approach that maximizes cumulative rewards by learning which actions lead to desirable outcomes.

Shade curtain: A greenhouse curtain designed to limit solar radiation received by plants.

Smart CEA environmental controls: Environmental—lighting; heating, ventilation, and air conditioning; or irrigation—controls for greenhouses or indoor farms that are capable of automation, integration, and/or artificial intelligence.

Sole-source lighting systems: Equipment delivering light to plants that do not also receive light from the Sun.

Substrate: The media used for growing plants, including soil, peat moss, coco coir, and rock wool.

Supplemental lighting systems: Equipment delivering light to plants in greenhouses during light-limiting conditions to increase crop growth.

Sunrise-sunset: Lighting control strategy where lights are gradually turned on and off over time rather than turned on instantaneously; this may include spectral tuning.

Value functions: A component of reinforcement learning providing a quantitative representation of expected cumulative rewards.

Vapor pressure deficit: A numeric value that calculates evapotranspiration potential CEA spaces based on space temperatures and humidity levels, measured in units of kilopascals (kPa).

Abbreviations and Acronyms

Acronym	Meaning
AI	Artificial intelligence
CalTF	California Technical Forum
CEA	Controlled environment agriculture
CEH	Controlled environment horticulture
CHP	Combined heat and power
CO_2	Carbon dioxide
CZ	Climate Zone
DAC	Disadvantaged communities
DLI	Daily light integral
EC	Electrical conductivity
EE	Energy efficiency
ePAR	Extended photosynthetically active radiation
ET	Evapotranspiration
EUI	Energy use intensity
FB	Feedback
FF	Feedforward
FR	Far red
ft^2	Square foot
GLASE	Greenhouse Lighting and Systems Engineering
HTR	Hard-to-reach
HVAC	Heating, ventilation, and air conditioning

Acronym	Meaning
IOU	Investor-owned utilities
kBtu	Kilo British thermal unit
kW	Kilowatt
kWh	Kilowatt-hour
LASSI	Lighting and shade system integration
LED	Light-emitting diode
MBH	Thousands of Btu per hour
ML	Machine learning
MPC	Model predictive control
NN	Neural network
PAR	Photosynthetically active radiation
PG&E	Pacific Gas & Electric
pH	Potential of hydrogen
PID	Proportional-integral-derivative
PPE	Photosynthetic photon efficacy
PPFD	Photosynthetic photon flux density
RH	Relative humidity
RL	Reinforcement learning
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
TPM	Technology Priority Map
VFD	Variable frequency drives
VPD	Vapor pressure deficit

Acronym	Meaning
VSD	Variable speed drives
VWC	Volumetric water content

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Introduction

This ET23SWE0067 CalNEXT project explored the market potential and evaluated the impact of smart controls technologies on controlled environment agriculture (CEA) through literature review, surveys, interviews, and site visits. The sections below provide an overview of the 2024 California CEA market, also referred to as controlled environment horticulture (CEH).

Horticultural lighting was identified as a high priority in the 2023 version of the CalNEXT Lighting Technology Priority Map (TPM) (CalNEXT 2023). The 2023 CalNEXT Process Loads TPM identified controlled environment food systems—such as efficient heating, ventilation, and air conditioning (HVAC) and irrigation controls—as a medium priority (CalNEXT 2023). Environmental controls were identified as an opportunity by the Lighting TPM for both energy efficiency (EE) and demand flexibility.

Market Overview

CEA is a segment of the agricultural industry where crops are grown under protection from outside conditions like wind, rain, and snow—either inside a building or within a boundary layer like a greenhouse—and which the United States Department of Agriculture defines as "under glass or other protection" (USDA 2024). The California Energy Code defines CEA facilities in three categories in the 2022 version of Title 24, Part 6: greenhouses, conditioned greenhouses, and indoor growing (CEC 2022). Greenhouses are growing facilities with a skylight-roof ratio greater than or equal to 50 percent, while conditioned greenhouses have heating systems with a capacity exceeding 10 Btu per hour per square foot, or cooling systems with a capacity exceeding 5 Btu per hour per square foot. Indoor farms are defined as a type of CEA space in a building with a skylight-roof ratio of less than 50 percent.

The benefits of CEA cultivation over conventional field farming are valued by growers, investors, and consumers (RII 2021). Additionally, industry stakeholders appreciate access to year-round crop harvests, enhanced product quality, water use efficiency, and increased canopy productivity (SCE 2021). A key benefit of CEA production is the decreased square footage required to grow crops when compared to field farming; for example, one acre of CEA food farming can achieve the same production capacity as a 35-acre field and produce 20 harvests per year (Quackenbush 2022).

In recent years, concerns about regional food systems, food security, water scarcity, global population growth, and impacts of more frequent and extreme weather events and natural disasters due to climate change have driven more growers to use CEA for stable and resilient production (Morlino 2024). However, CEA "can also create inequalities if it remains out of reach for some, especially small-scale and female agricultural producers" (FAO 2022). The development of incentive programs and investor-owned utilities (IOU) support systems can help to reduce barriers to adoption of advanced controls systems for these hard-to-reach (HTR) or disadvantaged producers, addressing inequalities within the CEA industry (RII 2021a).

More greenhouses and indoor farms are being built in California to meet increasing demand for a consistent supply of high-quality horticultural products. In 2024, there were 4,611 active California CEA operations growing food, floriculture, and cannabis (USDA 2024, DCC 2024). The number of

California CEA farms has grown considerably since 2017, when there were only 2,464 non-cannabis CEA operations (USDA 2019).

Figure 1 shows the distribution of California CEA operations by crop type, including floriculture, cannabis, and food crops. The cannabis license data reflects active licenses as of March 2024 (DCC 2024).

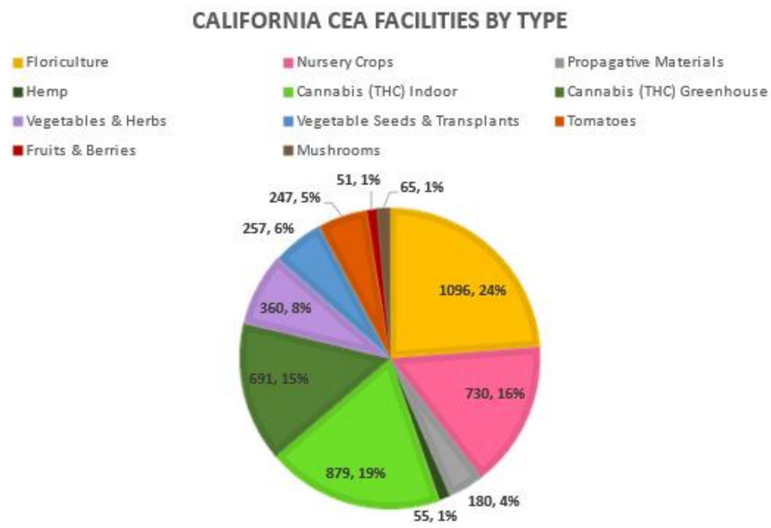

Figure 1: California CEA farms by crop type.

Source: USDA 2024; California DCC 2024.

Figure 2 describes the footprint of the California CEA industry in square feet, illustrating that there are 313 million square feet—or 7,185 acres—of greenhouses and indoor farms in California. 61 percent of every square foot of a CEA facility in California is for greenhouse floriculture or nursery crop production.

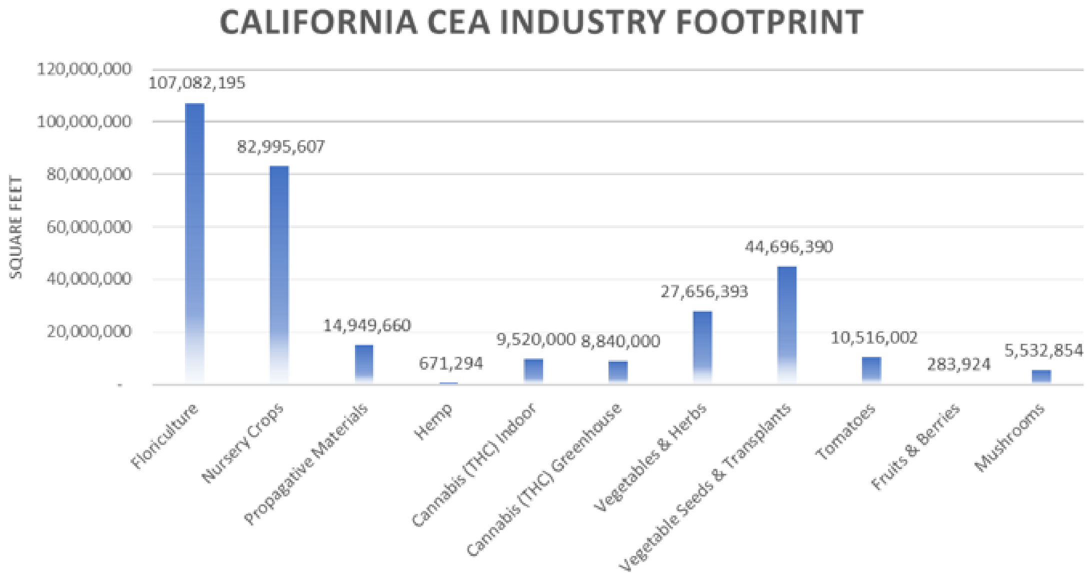

Figure 2: California CEA facility square footage by crop type.

Source: USDA 2024; California DCC 2024.

California CEA Floriculture and Nursery Production

As the "flower garden" of the United States, California produces 20 percent of the nation's nursery and floral products (CalFlowers 2021, Carman 2020), with floriculture sales surpassing $3 billion in 2024 alone (USDA 2024). Floriculture and nursery crops account for 61 percent of California CEA facility area, with 34 percent accounting for floriculture and 27 percent for nursery crops. CEA operations growing propagative materials—such as bare-root divisions, cuttings, liners, plugs, seedlings, tissue culture, plantlets, and prefinished—make up 14 percent of a California CEA facility area.

California CEA Cannabis and Hemp Production

Adult-use cannabis was the state's eighth most valuable crop in 2022, with a market value of $1 billion (Leafly 2023). However, that value dropped by 26 percent from 2022 to 2023 due to a surplus of product decreasing wholesale prices (Yakowicz 2023). Simultaneously, the cultivation canopy shrunk by 15 percent, with competition from the illicit market increasing while state taxes squeezed growers and economic conditions worsened (Schaneman 2023). The active commercial cannabis cultivation license count (which includes indoor, mixed light, and outdoor growers) decreased by 60 percent—from 5,481 in November 2023 to just 2,210 in March 2024—due to a 76 percent dip in active outdoor licenses (DCC 2024). While cannabis and hemp cultivators operate 34 percent of California CEA farms, they accounted for only 6 percent of the state's CEA farm area in 2024.

The California Department of Cannabis Control licenses greenhouse facilities as either Tier 1 or Tier 2 mixed-light operations, which are defined by lighting systems: Tier 1 operations may use up to 6 watts of artificial light per square foot, and Tier 2 operations may use between 6 and 25 watts of artificial light per square foot (DCC 2024a).

Indoor and Tier 2 mixed-light commercial California CEA cannabis licenses accounted for 57 percent of the 2,210 active licenses in 2024 (DCC 2024). Greenhouse licenses decreased by 47 percent between November 2023 and March 2024, while indoor license counts remained stable. See Appendix A: California Cannabis Licensees by County for a table of California indoor and greenhouse cannabis licensees by county. Los Angeles County has the greatest concentration of indoor cannabis licensees and Monterey County has the greatest concentration of Tier 2 mixed-light greenhouse cannabis licensees.

The illicit cannabis market in California may still comprise a substantial portion of the state's cannabis industry; however, the market's proportion of indoor and greenhouse operations is unknown.

California CEA Food Crop Production

California has the largest greenhouse vegetable industry in the United States, with the market value of CEA vegetables and herbs growing by 42.3 percent between 2017 and 2022 (USDA 2019, USDA 2024). While California's temperate climate can be ideal for field farming of many crops year-round, 723 California CEA operators grow food crops—such as vegetables and herbs, tomatoes, fruits and berries, and mushrooms—in greenhouses or indoor farms, which account for 14 percent of the total CEA farm area. This includes 9 percent of the CEA farm area for vegetables and herbs, 3 percent tomatoes, and 2 percent for mushrooms.

Background

This study focuses on opportunities for smart CEA environmental controls strategies to reduce the energy consumption driven by three CEA process systems for optimizing climate control and plant production: horticultural lighting, HVAC, and irrigation.

The following section describes the energy consumed by CEA facilities, explores CEA controls technology components and decision-making logic, and examines the energy saving potential of various CEA controls measures.

CEA Facility Energy Consumption

A principal drawback of industry standard methods for CEA cultivation is the energy consumption required to operate process systems for climate control and plant production, which accounts for up to 60 percent of greenhouse or indoor farm operating costs (ACEEE 2019). CEA facilities in general can have large environmental impacts due to energy use from process systems like lighting and HVAC. Specifically, the energy intensity within California CEA operations can be between 40 to 150 kWh per square foot based on plant-specific parameters, such as crop type and number of racks for vertical farms, lighting and HVAC equipment efficiency rating, and controls characteristics like lighting schedules and temperature setpoints (SCE 2021).

A study surveying 336 global CEA facility operators in 2021 found that vertical farms use 39 kWh per kilogram of harvested crop, on average. Respondents reported that on average, 34 percent of energy use for CEA operations is driven by HVAC, while an average of 33 percent is driven by lighting—but these systems direct energy use very differently for greenhouses and indoor farms (WayBeyond and Agritecture 2021). Figure 3 below shows responses for greenhouses, labeled as GH in yellow, and indoor vertical farms, labeled as VF in green. Greenhouse energy use is predominantly driven by cooling, ventilation, and mechanical motors for running irrigation pumps and horizontal airflow fans, while indoor vertical farm energy use is primarily driven by lighting systems. Energy consumption associated with horticultural lighting can represent up to 30 percent of the operational costs in lit greenhouses (GLASE 2024).

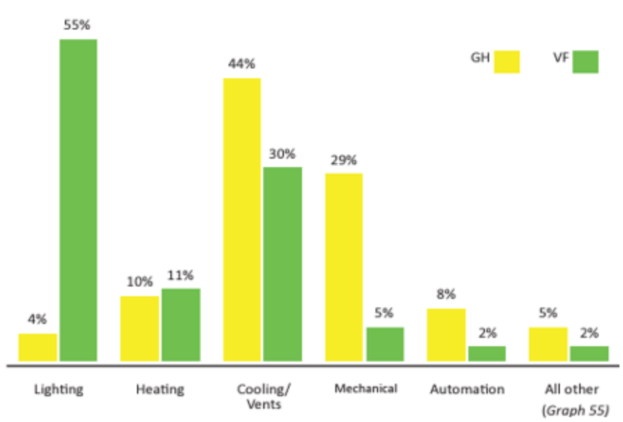

Figure 3: CEA facility energy end uses.

Source: WayBeyond and Agritecture 2021.

Detailed energy use information for US CEA facilities is hard to come by, and researchers have found that many CEA companies are reluctant to share this data (Phillips 2024). A national sample of five indoor farms and seven greenhouses described benchmarks for EE in kBtu per square foot and energy productivity in kBtu per pound of fresh produce, accounting for all energy sources like electricity, natural gas, and delivered fuels (RII 2023). However, this report did not include any facilities in the state of California.

Lighting systems can account for 30 to 50 percent of electricity usage for California indoor farms (SCE 2021). Figure 4 describes the proportion of electricity usage driven by horticultural process equipment: lighting, heating, ventilation, dehumidification, air conditioning and cooling, irrigation, and miscellaneous systems like carbon dioxide (CO_2) enrichment.

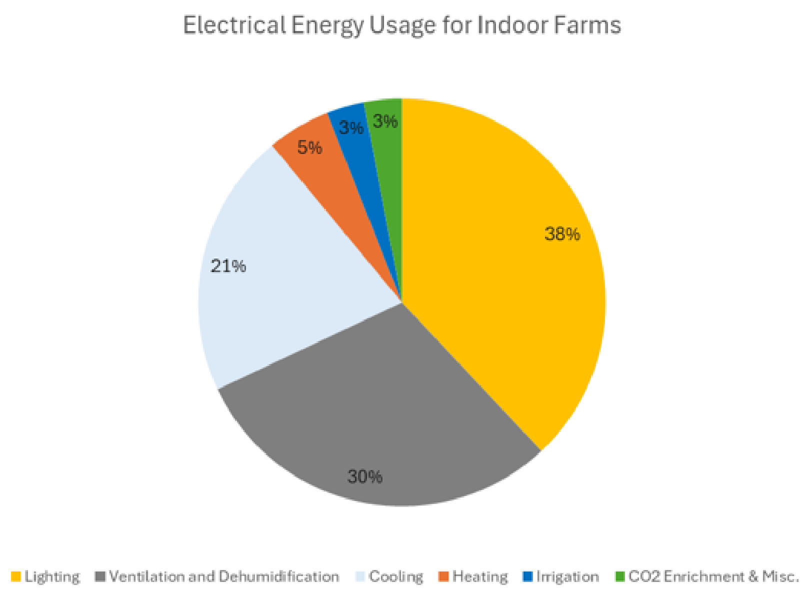

Figure 4: Indoor farm electrical end uses.

Source: SCE 2021.

The energy consumption of CEA facilities is highly dependent on system design decisions around lighting, HVAC, and CO_2 enrichment, with the most energy efficient scenarios consuming 46 to 49 percent less energy than the least efficient scenario (Eaton et al. 2023).

CEA Controls and Automation

Process equipment, which contributes to the bulk of the energy consumption in CEA facilities, can be operated manually or be automated with a control system.

These process system controls incorporate diagnosis via sensors that monitor real-world conditions and decision-making through software programs that evaluate sensor data and implement control sequences of operation.

Sensing and Monitoring

CEA control systems monitor and evaluate actual conditions reported by sensing equipment in cultivation spaces before controlling a process system—lighting, HVAC, or irrigation—to maintain standard operating procedures for a facility, e.g., target light intensity, space temperature, relative humidity, and soil moisture content. Sensors can be of varying accuracy and durability; while residential-grade sensors are not suitable for CEA applications, business-grade, industrial-grade, and scientific-grade sensors can perform in harsh conditions, such as space temperatures exceeding 90°F and relative humidity ratios exceeding 90 percent of a greenhouse or indoor farm. Sensor quality can be distinguished with International Electrotechnical Commission ratings like ingress protection.

CEA controls can use wired or wireless sensors; the value proposition depends on the application. Wired sensors offer reliability and stability, with consistent connectivity and low latency, making them suitable for environments where real-time data transmission is crucial. Wired sensors also benefit from a continuous power supply, high data transmission rates, and enhanced security, so the sensors can serve scenarios where consistent and secure data flow is crucial. However, the wired sensors deployment can be costly and complex over large areas.

Wireless sensors support smart environmental controls applications in CEA operations well due to their long-range capabilities and low power consumption, which allow the sensors to transmit data over several kilometers and operate for years on a single coil cell battery. Wireless sensors can be more cost-effective for monitoring extensive fields, as they eliminate the need for extensive cabling and simplify installation and maintenance. Additionally, the scalability and flexibility of wireless sensors support rapid deployment and integration into diverse ecosystems, enabling efficient remote monitoring of agricultural resources like energy and water.

While both sensor types have distinct advantages, wireless sensors are particularly useful for large-scale, dispersed, and remote agricultural applications, enhancing the efficiency and sustainability of smart farming practices (Microclimates 2024).

Automation

Automation can be defined by levels of increasing system controllability, connectivity, and intelligence. The five major categories of CEA controls are described below in Table 1. At Level 0, a human operator completes diagnosing the current system status, decides what action to take, and controls the process systems. At Level 4, diagnosis, decision-making, and automation are all autonomously performed by hardware and software. While Manual and Basic controls—Levels 0 and 1 respectively—are the most common and least costly, Automated, Integrated, and Intelligent controls—Levels 2 through 4—are scalable and can manage multiple process systems; both characteristics are key to advancing CEA resource efficiency. Manufacturers of Automated, Integrated, and Intelligent smart control systems provide a universal platform for growers to reduce costs, maximize efficiency, and increase crop value (Microclimates 2023). For this study, smart CEA environmental controls are defined as Levels 2, 3, and 4 in Table 1 below.

Table 1: Categories of CEA process system controls.

Categories of Control Technology	Energy Savings Potential	Technology Scope
Level 0: Manual control	Lowest	Manual controls include on/off switches and allow growers to maintain system setpoints with a human touch.
Level 1: Basic control	Low	Basic controls include programmable thermostats and timers and allow growers to vary system setpoints and schedules independently at a system level, using simple hardware that reports actual conditions in the cultivation space.
Level 2: Automated controls	Moderate	Automated controls include standalone controls, like step controllers, and remotely monitor and control system setpoints and schedules independently at a system level. They use sensors that report actual conditions in the cultivation space.
Level 3: Integrated controls	High	Integrated controls include connected monitoring and automation systems exchanging information between multiple types of process equipment. They remotely monitor and control system setpoints and schedules across two or more process systems, using sensors that report actual conditions in the cultivation space.
Level 4: Intelligent controls	Highest	Intelligent controls use machine learning, artificial intelligence (AI), or data-driven logic to monitor conditions, determine setpoints and schedules simultaneously for all process systems using sensors reporting actual conditions in the cultivation space.

Source: RII. 2024. GLASE 2024.

Automated control systems for CEA lighting, HVAC, and irrigation equipment can comprehensively improve facility performance; advanced control systems have been proven to raise productivity, increase system resilience, increase product quality, increase energy and water efficiency, and increase sustainability (RII 2021a).

CEA Controls Integration

Integrating control systems can not only optimize resource utilization but can also enhance system effectiveness and foster healthier plant growth (Iliev et al. 2013). Various environmental factors interact intricately to influence plant growth and productivity. Light received by plants directly impacts plant transpiration rates, which in turn affects the amount of water required for adequate irrigation. Further, leaf water transpiration contributes to changes in atmospheric relative humidity, which is inversely related to temperature. These interdependencies highlight the necessity of integration between environmental control systems in CEA, and failure to consider these interactions leads to inefficiencies or counterproductive outcomes.

Integrated systems often categorize input and outputs—or controlled variables—into the following three categories: Atmospheric, Lighting, and Irrigation/Fertilization. In this study, these system categories are referred to as HVAC, Lighting, and Irrigation. The input variables, described in Table 2 below, can be fed into combinations of automation loops and controls, allowing one system to inform the operation of another.

Table 2: CEA process system controls variables.

System Category	Variables
HVAC	Space temperature, space relative humidity, air speed, space CO_2 concentration, leaf temperature, substrate (grow media) temperature.
Lighting	Total light intensity received from the Sun, total light intensity from electric lighting systems, spectral treatment.
Irrigation	Substrate moisture content, substrate potential of hydrogen (pH), substrate electric conductivity (EC), nutrient solution pH, nutrient solution EC, root zone temperature.

Source: RII 2021a.

Decision-Making Logic for Automated CEA Controls

HVAC, and other CEA facility systems like lighting and irrigation, are typically automated using a hierarchical control structure designed to achieve horticultural objectives, such as maintaining temperature within a cultivation space. Local-loop control may control a single setpoint while supervisory control may specify setpoints and implement schedules, monitor energy usage, or reduce peak demand to decrease energy costs (ASHRAE 2019).

Automated control approaches vary widely and can use various logic models. The most notable models employed for CEA process system automation at Level 2 control are decision trees, proportional-integral-derivative (PID) control, and model-predictive control (MPC).

DECISION TREES

Decision trees are the simplest form of logic for automated CEA controls where data inputs are interpreted by if-then-else decision rules to predict output variables. This logic model can also be described as a piecewise constant approximation. Decision trees can accept qualitative and quantitative data and are highly adaptable to diverse applications, but they often output yes/no decisions. Given the simplicity of the logic, decision trees are not continuous and are poor extrapolators and poor interpolators (Breiman et al. 1984). However, decision trees are easy for CEA operators to interpret and visualize, increasing accessibility to growers with little to no controls experience. This allows growers to independently update decision tree programming settings.

PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) CONTROL

PID controllers first emerged in engineering science in the early 1940s and became popular for industrial and military applications after the advent of digital computers in the 1950s (Minorsky 1942, Ogata 2010). Figure 5 below describes the logic model for PID controllers.

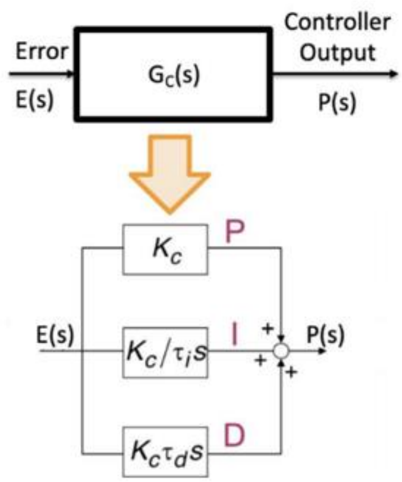

Figure 5: PID control logic.

Source: CalTech 2004.

Figure 5 illustrates how data inputs are translated into controller outputs by PID control algorithms. An error term (E(s)) is continuously calculated as a deviation of real-time sensor readings from an established setpoint. This is fed into the gain function (G(s)), which is comprised of three responses: a proportional, an integral, and a derivative piece. K_C and τ_x represent the response gains and time constants, respectively, and the sum of these three responses represents the controller output (P(s)). These terms may be used separately or in various combinations, depending on the needs of the system (Schneider Electric 2020).

The PID controller is one of the most widely used control algorithms in the buildings industry, and the control's versatility and robustness have made it a standard tool for controls engineering. Despite advances in technology, the PID controller remains a popular and effective control algorithm due to the simplicity, ease of implementation, and ability to provide satisfactory control in a wide range of industrial processes.

PID algorithms are used in feedforward (FF) or feedback (FB) loops, and are usually combined for performance and stability. FF measures disturbances before they affect the system and controls accordingly, while FB measures disturbances in the output of the controlled variable and adjusts the control accordingly. When used in conjunction, FF and FB loops using PID controls offer robust performance and stability.

Climate control is a good example of FF control applied to CEA facilities, where sensors can monitor actual greenhouse conditions to control horticultural lighting systems, HVAC equipment, motor-controlled vents and shading curtains, and irrigation valves. This allows the system to maintain target environmental conditions, such as space temperature and relative humidity (Kolokotsa et al. 2010).

MODEL PREDICTIVE CONTROL (MPC)

Model-predictive control (MPC) is an optimizing logic model that minimizes a cost function for a constrained system over a finite time horizon. The MPC algorithms are currently the most highly researched control systems in greenhouse applications, and are designed to minimize energy consumption, maximize profit, and maximize crop quality (Wageningen University 2022).

MPC models continuously solve an open-loop optimization problem for a predefined system function over a specified prediction horizon. At each time step, MPC predicts the future behavior of the system based on the current state and applies control actions derived from the optimization solution. Following the application of these controls, MPC reassesses the system state, adjusts the prediction horizon, and reiterates the optimization process to generate new control actions for the next time step. This iterative approach allows MPC to adaptively respond to changes in the system dynamics and environmental conditions, thereby optimizing control actions in real-time (Anderson et al. 2024). This control logic is demonstrated in Figure 6, with "RHC" signifying the receding horizon control.

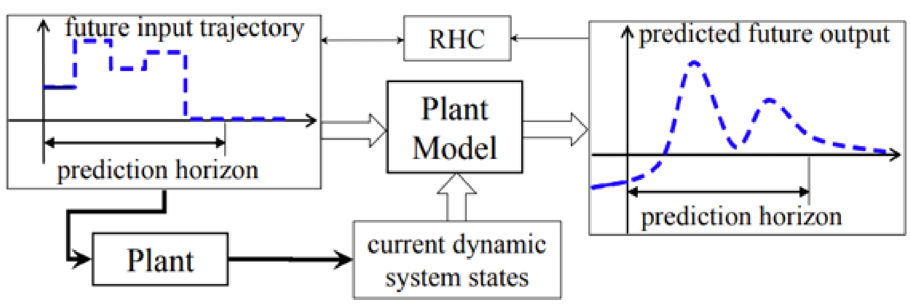

Figure 6. MPC control logic.

Source: Farag 2019.

An advantage of MPC is the ability to anticipate future disturbances and incorporate them into the control strategy, allowing for proactive responses to changing system conditions. Unlike other automated CEA control strategies, MPC can handle non-linear systems and can optimize multiple objectives simultaneously. Further, the model can explicitly consider physical, safety, or operational constraints, ensuring that control actions remain within acceptable bounds (Ibid.).

However, despite these strengths, there are several drawbacks to MPC. MPC logic for greenhouses depends on reliable and accurate weather forecast data. The computational complexity of solving optimization problems at each time step is significant and can incur long calculation times and high costs, and uncertainty in model parameters or disturbances can lead to inaccuracies and instability.

Selecting an appropriate prediction horizon is necessary for MPC operation but can be challenging and require iterative tuning (Ibid.).

Decision-Making Logic for Integrated CEA Controls

Advanced control approaches integrate systems together. The most notable models employed for the Level 3 control CEA process system integration is fuzzy logic.

FUZZY LOGIC

Fuzzy logic is a methodology for variable processing that accommodates multiple possible truth values within the same variable. Models with fuzzy logic are capable of recognizing, representing, manipulating, interpreting, and then using vague or uncertain data, which is especially important in integration, where multiple true optimums may exist across systems. The addition of fuzzy logic to integrated controls allows for adaptivity and flexibility, allowing input and optimization of several different systems at once, and it also accounts for the nonlinearity and complexity of crop dynamics, which can be unknown and change rapidly. Fuzzy logic also increases computational speed and allows for the integration of non-numerical human expert knowledge to be incorporated into the controls (Iliev et al. 2013).

This increase in complexity does come at a cost; fuzzy logic excels in handling imprecise and uncertain data, and therefore is not optimal for precision controls. Further, the training and tuning required for the model requires significant effort when selecting appropriate variables, functions and rule sets, and fine-tuning parameters.

Decision-Making Logic for Intelligent CEA Controls

The most sophisticated logic models apply machine learning (ML) to integrated and automated control systems. Models of CEA process systems at Level 4 control use neural networks (NN) and reinforcement learning for intelligent decision-making.

NEURAL NETWORKS (NN)

Inspired by the structure and function of the human brain, neural network ML model systems consist of interconnected nodes, or neurons, which are organized in layers and linked by weighted connections. Each neuron receives input data, performs a mathematical operation, and passes the result through the weighted connections to the next layer. Through a process called training, NNs learn to recognize patterns and relationships in an example dataset and adjust the weights of each connection to reflect these patterns. Trained NNs can complete classification, regression, and pattern recognition tasks (Albahar 2023).

A 2023 study employed the use of an NN controller to achieve desired photosynthetic photon flux density (PPFD) levels in a greenhouse cultivating lettuce, training it using one year of historical solar data. During the testing phase, the AI-based controller optimized lighting schedules and spectral treatment based upon sunlight received by plants. This strategy was proven to reduce the energy consumption of lettuce production by 28 percent per dry mass when compared to conventional scheduling methods, while also mitigating plant issues such as tip burn. The study built upon this result and developed a plant growth model-based optimization technique to determine the ideal lighting schedule within a dynamic power market. The incorporation of power market data within the NN saved 40 to 52 percent of energy expenses within a simulation scenario. Further, the researchers investigated the impact of controlled and targeted light emitting diode (LED) lighting on energy consumption. They found that the optimization of spectral parameters for close-canopy LED lighting can achieve lighting system energy savings of 50 percent (Mohagheghi and Moallem 2023).

While NN controllers are highly powerful and can lead to significant energy savings in CEA, there are a few key drawbacks. The controller's black-box nature can make it challenging for growers to interact with the system and interpret the decision-making logic. Further, NNs require large amounts of labeled data for training before they can operate a system and are very computationally intensive. This can be a barrier in smaller-scale operations with limited historical data (Tu 1996). One way to overcome this hurdle is to apply AI to train the model by using algorithms to teach the NN logic (Hoogendoorn 2024).

REINFORCEMENT LEARNING (RL)

Reinforcement learning (RL) is a type of ML model focused on decision-making and control through a feedback-based approach. In RL, a program learns to interact with an environment by taking actions and receiving feedback in the form of rewards or penalties. The goal of the program is to maximize cumulative rewards over time by learning which actions lead to desirable outcomes. RL algorithms use trial and error to discover effective strategies, using techniques such as value functions, policy gradients, or Q-learning. Value functions provide a quantitative representation of expected cumulative rewards, while policy gradients help RL programs maximize expected rewards by following a policy (Kapoor 2018). Q-learning is a popular off-policy RL algorithm that uses an action value function—the Q-function—to learn an optimal policy; the Q-function is updated iteratively using the Q-learning update rule (Doshi 2020).

One advantage of RL comes from the significant opportunity for both energy savings and increased climate stability. The principal limitation of RL controls is the requirement for extensive exploration and trial-and-error prior to operation, which can be time consuming and costly. Further, if not properly designed, RL can introduce biases due to reliance on reward signals.

RL systems have already demonstrated efficacy in many agricultural controls systems, including lighting, irrigation, and HVAC (Bu and Wang 2019); for example, in 2023, researchers implemented an RL algorithm in a semi-closed tomato greenhouse and compared energy consumption and performance with a conventional MPC control strategy (Ajagekar et al. 2023).

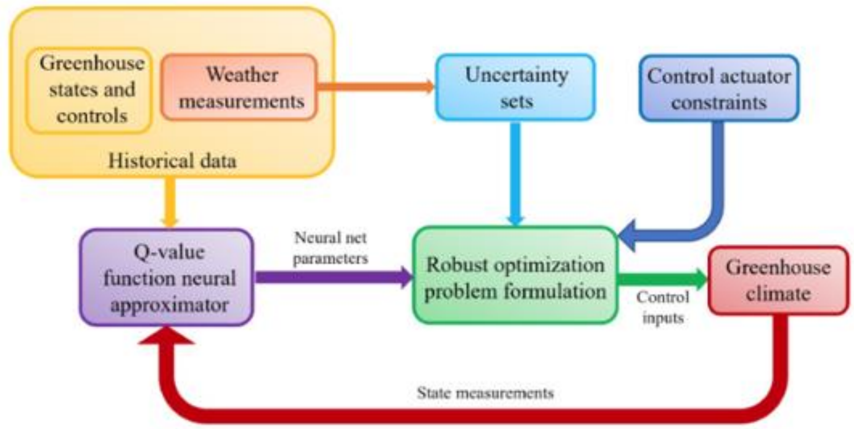

Figure 7: Robust optimization in deep reinforcement learning.

Source: Ajagekar 2023.

The system was used in conjunction with an NN system that estimates the greenhouse's real time energy consumption, given training from historical data and current climate measurements. This consumption value is then fed to the RL decision-maker, which employs an adaptive approach to learn from the determined climate trajectories and to minimize energy consumption while meeting required climate conditions. The RL outputs controlled actuators in HVAC and lighting systems, the logic of which is depicted above in Figure 7.

After a ten-week tomato growth cycle, the RL system decreased facility energy consumption by 57 percent from a baseline of 79,258 kWh with an MPC controller. The RL controller also maintained a more consistent air temperature at the desired setpoints—an improvement over MPC systems, which tend to overshoot temperatures by 9 to 13°F, or 5 to 7°C.

CEA Controls Measures by Process System

Automated CEA process equipment can reduce the energy consumption of CEA facilities using various control strategies. The energy savings potential of controls measures can be application-dependent; some measures are suitable for both greenhouses and indoor farms, but some may only apply to one type of CEA facility.

Figure 8 describes the ideal environmental conditions for 11 crops that can be grown in CEA facilities. Note that some crops require different environmental conditions by stage of plant growth or during day or night conditions. These target conditions drive energy consumption of horticultural lighting, HVAC, and irrigation equipment.

	Temperature (Celsius)	Relative Humidity	VPD	Lighting Density	Photo-period	CO_2 Concentration	Cultivation Period (Days)
Lettuce [20,34, 45]	25 °C (Day); 22 °C (Night)	60–70%	0.85–0.95	200 PPF	16 h	800–1200 ppm	30
Tomatoes [20, 34,35]	25 °C–31 °C	75%–85% vegetative; 65%–75% for flowering	0.65–0.8 vegetative; 0.85–1.0 flowering	600 PPF	12 h	1000 ppm	90
Herbs [46,47]	20 °C (Day); 15 °C (night)	70–80%	0.6 (Day); 0.45 (Night)	67% red at 620 nm; 33% blue light at 450 nm	12 h	800–1200 ppm	50 - 90 depending on variety
Micro-greens [35,48,49]	21 °C (Day); 17 °C (night)	80%	0.5 (Day); 0.39 (Night)	85% red, 15% blue; 300–600 PPF depending on variety	16 h	500–800 ppm	7 - 21 depending on variety
Shiitake Mushrooms [29,36]	12.8 °C–24 °C	85% early on. Can drop to 60% after 3 days of pinning, but 80% is ideal.	0.6–0.8	55 - 100 PPF	12 h	800 ppm (6–10 air changes per hour to keep CO2 levels low)	50–60
Cannabis [34, 41,42]	22 °C–30 °C	65%–75% vegetative; 60%–70% flowering; 55%–65% stressing	0.80–0.95 vegetative; 1.0–1.15 flowering; 1.16–1.35 stressing	400 - 600 PPF	18 h veg; 12 h flowering	800–1100 ppm	70–80
Cucumbers [[34,43,51]	21 °C–25 °C (Day); 20 °C (Night)	75–80%	0.65 (Day); 0.45 (Night)	100 PPF early stages; 250 ppf mature; 85% red, 15% blue	16 h	450–600 ppm	55–65
Peppers [50,52, 53]	21 °C (Day); 17 °C (Night); 16 °C (flowering)	55–65%	3 - 5 seeding; 1.0 (Day), 0.75 (Night) vegetative	430 - 500 PPF	18 h seed; 14 h veg	450–500 ppm	50–65
Strawberries [20,34]	30 °C (Day); 15 °C (Night)	65% (day); 100% (night)	1.0 (day); 0.0 (night)	300 PPF (red light)	16 h	1000 ppm	90
Blueberry Transplants [20]	23 °C average	90%	0.28	100 - 200 PPF	16 h	1500 ppm	30–40
Rice [20]	23 °C–27 °C	70%	1.05 (day); 0.85 (Night)	800 PPF	12 h	400 ppm	100

Figure 8: Target environmental conditions for CEA crops.

Source: Engler and Krarti, 2021.

Energy savings for some CEA controls measures can be interactive, and are significantly influenced by crop type or climate zone (CZ). Validating energy savings may require energy modeling or energy monitoring—which can vary by manufacturer and level of system integration—to measure and verify actual energy savings for California facilities (Schimelpfenig 2023).

The following sections explore the major energy-saving opportunities presented by automated, integrated, and intelligent horticultural lighting controls, horticultural HVAC controls, and horticultural irrigation controls.

Horticultural Lighting Controls

Horticultural lighting systems are used in greenhouses to supplement sunlight and typically appear in indoor farms to provide sole-source lighting for plant growth and development. Light fixtures are most often top canopy fixtures, but some growers use intercanopy lighting systems to increase light levels within lower elevations of plant canopy. Horticultural light fixtures primarily focus on delivering light within the photosynthetically active radiation (PAR) spectrum, which corresponds to photons from the 400 to 700 nanometer (nm) wavelengths (RII 2023a). Some fixtures deliver light within the extended PAR (ePAR) spectrum to provide far red (FR) photons.

Energy consumed by horticultural lighting systems is driven by photosynthetic photon efficacy (PPE), measured in units of µmol/J. LED horticultural lighting technology provides improved efficiency and controllability over legacy horticultural lighting technology, such as high-pressure sodium and fluorescent (GLASE 2021).

Fixed-spectrum light fixtures use various designs combining colors of diodes like white, red, green, blue, and far red to provide custom "light recipes." Some "full spectrum" or "broad spectrum" fixtures incorporate white diodes, which provide a mixture of blue, red, and green wavelengths. A light recipe may use large amounts of red between 65 and 80 percent, some green around 20 percent, and blue around 5 to 30 percent to achieve plant quality attributes like reduced plant height. Some light recipes incorporate far red light around 10 percent to accelerate plant activity, like stretching or flowering, or use ultraviolet radiation around 5 to 10 percent to improve plant resilience, regulate plant growth, and general crop quality.

An example fixed-spectrum light recipe is B20:R80, or 20 percent blue, 80 percent red light. Figure 9 below demonstrates the theoretical maximum PPE of around 5 µmol/J for LED horticultural light fixtures, with a 20 percent blue and 80 percent red light recipe. However, by 2040, B20:R80 horticultural LED fixtures available on the market are likely to plateau at around 4.5 µmol/J.

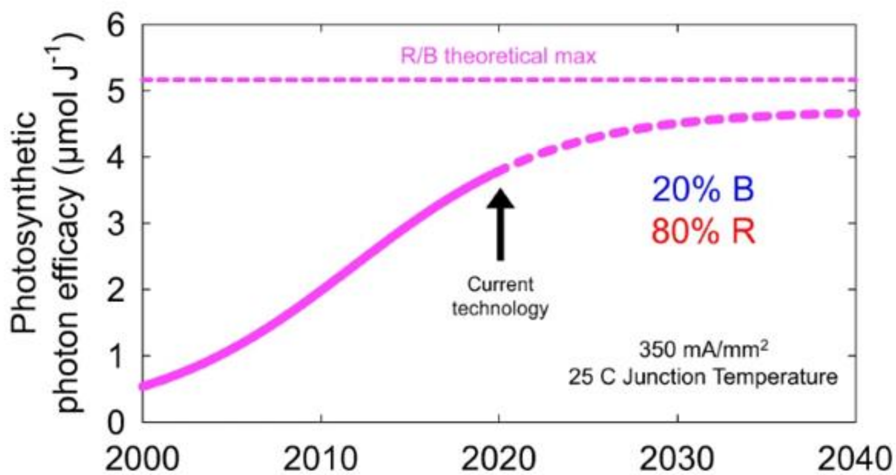

Figure 9: Historical, current, and projected LED package efficacy.

Source: Kusuma et al., 2020.

In California, LED horticultural lighting is close to becoming industry standard practice for both greenhouses and indoor farms, as it already is for stacked vertical farms as of 2024 at 2.52 µmol/J, with the expectation that it will rise to 2.56 µmol/J in 2025, for both greenhouses and single-layer indoor operations (DNV 2023).

Title 24, Part 6 of California's energy code currently requires horticultural lighting systems in CEA facilities to maintain a PPE of 1.7 µmol/J for greenhouse supplemental lighting systems, with 1.9 µmol/J for indoor farm sole-source lighting systems in the 2022 version of the code (CEC 2022). The proposed 2025 version of the code requires 2.3 µmol/J for lighting systems serving both greenhouses and indoor farms (CEC 2024). These requirements only apply to facilities with more than 40 kW of total connected horticultural lighting.

Industry standards for horticultural lighting controls are nascent, and industry groups like the DesignLights Consortium's (DLC) Horticultural Lighting Controls Working Group are gathering expert input on ways to craft technical requirements and a qualified products library for networked horticultural lighting solutions (DLC 2024a). Dimming, scheduling, spectral tuning, integration, and interoperability are all areas that may be addressed with horticultural lighting controls technical requirements in the near future.

Advanced horticultural lighting controls can significantly reduce energy usage and operating costs for both greenhouses and indoor farms (GLASE 2023). The sections below describe dimming and daylighting, the primary energy-saving measures presented by horticultural lighting controls, while Table 3 summarizes the control parameters and units measured by CEA lighting automation systems.

Table 3: CEA lighting automation strategies.

Control Strategy	Control Parameter	Unit Measured
Dimming Controls	PAR light intensity	PPFD, μmol/m²/sec
Spectral Tuning	Proportion of PAR and ePAR wavelengths	Peak wavelength, nm PPFD, μmol/m²/sec
Daily Light Integral (DLI) Controls	PAR light received per day	DLI, mol/m²/day

Source: ERI. 2024c.

The following sections describe the energy savings potential of each of the above lighting control strategies in more detail.

DIMMING CONTROLS

Dimming controls for horticultural lighting systems adjust power to sole-source and supplemental lighting systems to achieve a target PPFD value, which is a measure of the amount of PAR received by plants measured at a single point and averaged across plant canopy area. Dimming controls allow sole-source lighting systems to precisely deliver target light levels to plant canopies (RII 2024) and supplemental lighting systems to avoid over-lighting crops—meaning providing light even though photosynthesis is already saturated—by complementing sunlight received in greenhouses (GLASE 2024a).

Tailoring light levels to the cultivar by stage of plant growth allows CEA facilities to save energy by up to 20 percent with dimming controls, usually done through photoacclimation strategies (GrowFlux 2023 and RII 2024). By gradually adjusting light intensity as plants grow week by week, plants can develop stronger root systems, resulting in higher nutrient uptake and increased growth (Bugbee 2016).

Horticultural lighting can also be dimmed daily using sunrise-sunset sequences of operation, where lights are gradually turned on and off over time rather than turned on instantaneously. Some systems can also change spectral treatment concurrently with light intensity to mimic solar light quality. For example, a sunrise sequence of operation can start with a warm, low white light and will gradually increase in intensity while the spectrum changes to a colder white light during the day; a sunset controls sequence does the reverse, from cold white to warm white spectral treatments (Sollum Technologies 2024).

Non-energy benefits of sunrise-sunset dimming controls include better maintenance of temperature and humidity during transitions between lights on and lights off periods. When lights switch on/off without a gradual transition, humidity levels can spike because of plant transpiration driving an increase in latent heat, which also imposes energy loads on climate control systems. Therefore, the energy reduction from dimming offers interactive HVAC savings, and smoothing transpiration rates between lights-on and lights-off periods also has non-energy benefits, reducing the risks of disease like botrytis or powdery mildew.

Energy savings from dimming controls operates as a function of both behavioral inputs and fixture characteristics. For example, when dimming to 50 percent to reduce output power, the efficacy of a lighting module also can increase by 8 percent (Philips 2024), as described in more detail in Table 4 below.

Table 4: Impact of horticultural dimming control on fixture photosynthetic photon efficacy (PPE).

Dimming Setting	Dimmed Fixture PPE (Input PPE = 2.0 µmol/J	Dimmed Fixture PPE (Input PPE = 2.5 µmol/J	Dimmed Fixture PPE (Input PPE = 3.0 µmol/J
0% (Full Power)	2.0	2.5	3.0
50% (Half Power)	2.16	2.7	3.24

Source: Philips. 2024.

The efficacy increase from dimming depends on many parameters such as LED driver design, fixture manufacturer, mechanical design of the fixture, fixture heat dissipation efficacy, and temperature of the LED components. For instance, the hotter an LED component is, the less efficient it becomes. If fixtures are dimmed but the temperature of the fixture does not decrease, there will be less or even no efficacy gains (Sollum Technologies 2024).

Dimming energy savings are also crop-dependent and application-specific; magnitude of savings will vary depending on facility type, light fixture wattage, and stage of plant growth, which influences hours of lighting system operation. The savings potential is greatest for facilities using high-output lighting systems to grow plants like cannabis, cucumbers, tomatoes, and peppers (RII 2024). Energy savings from horticultural dimming strategies, like photoacclimation and sunrise-sunset, can be applied to both sole-source lighting systems in indoor farms and supplemental lighting systems in greenhouses. This report also explores other dimming control strategies, including a specific greenhouse dimming strategy called DLI controls, in future sections.

Other dimming controls work in the following ways:

- **Level 2**: May use light sensors to measure PPFD and automatically dim lighting system power according to a defined PPFD target and lighting schedule.
- **Level 3**: May use light sensors to communicate information with climate control systems, such as lighting schedules and dimming setpoints.
- **Level 4**: May use ML that accesses historical data or real-time data, such as images from plant cameras, to determine light level targets for dimming sequences of operation.

Dimmable horticultural lighting systems are not yet industry standard practice in California due to increased cost and complexity compared to basic lighting systems, but they are becoming more widely adopted as manufacturers produce more dimmable fixtures. Version 3.0 of the DesignLights Consortium's (DLC) Horticultural Technical Requirements, effective March 2023, updated controllability requirements to mandate dimming capabilities (DLC 2023), and delisted Version 2.1 products were delisted in March 2024 (DLC 2024).

SPECTRAL TUNING

LED horticultural light fixtures can be tuned to adjust light quality throughout the day or dynamically change throughout stages of plant growth and development. (GLASE 2024b).

Spectral tuning is the modulation of output from the different diodes on LED fixtures, tailoring the number of photons from each wavelength to influence plant quality attributes such as stem elongation, leaf size, flower development, fruit yield, and harvest cycle length. This tuning is not limited to specific colors, nor limited by a certain number of LED channels (Sollum Technologies 2024, and dynamic light fixtures can adjust spectral output and provide unlimited combinations of wavelengths to provide infinitely customizable light recipes (GLASE 2024b). Additionally, growers can use spectral tuning to achieve the specific solar light spectrum and photoperiod from any location in the world at their farm (Sollum Technologies 2022).

Light fixtures incorporating a large proportion of red will achieve higher PPE and can reduce energy usage (RII 2024), but the larger the proportion of red is for a horticultural light fixture, the less flexible in spectral tuning the light fixture will be. This will limit the potential energy savings from different spectral tuning strategies (Sollum Technologies). Tuning light recipes must be done with care; changing the red/blue ratio can trigger specific photomorphogenic responses, such as stem elongation and shade avoidance, which may be undesirable (GrowFlux 2024).

As with the dimming schedules mentioned in the previous section, spectral tuning levels can work in the following ways:

- **Level 2:** May use timeclocks to tune lighting spectrum according to a defined lighting schedule.
- **Level 3**: May use light sensors to communicate information with climate control systems, such as real-time spectral settings.
- **Level 4**: May use ML that accesses historical crop data to forecast the best spectral treatment for each crop based on stage of plant growth.

Table 5 below summarizes the efficiency of various wavelengths of PAR and far red (FR) light (Kusuma et al. 2022). The study describes typical performance of a range of high-performance LED fixtures with peak wavelengths across the photobiologically active range of radiation—280 to 800 nm. Spectral treatments with more red photons are more efficient at converting electricity to PAR than spectral treatments with more blue photons, but they address different agronomy objectives. For example, growers want to have a blue treatment a few days before harvesting red lettuce to improve the anthocyanin uptake in the leaves and increase the color pigmentation of the lettuce (Sollum Technologies 2024).

Table 5: LED luminaire photosynthetic photon efficacy by wavelength.

Color Name	Peak Wavelength	Photosynthetic Photon Efficacy (PPE) µmol/J
Blue	450 nm	2.8
Blue	470 nm	2.4
Blue	500 nm	2.0
Green	530 nm	1.3
Yellow / Amber	590 nm	1.1
Orange	620 nm	3.4
Red	635 nm	2.5
Red	660 nm	4.1
Far Red	730 nm	3.6
Far Red	850 nm	3.0

Source: Kusuma et al. 2020; RII 2024.

Table 6 below compares five light fixtures from three manufacturers to demonstrate variability in efficacy by light recipe, compared against the 2025 California energy code proposed minimum PPE of 2.3 µmol/J for greenhouses and indoor farms. Spectral tuning controls that incorporate more output from red diodes and less output from white or blue diodes can result in significant energy savings from lighting.

Table 6: Spectral tuning energy savings.

Light Recipe	Photosynthetic Photon Efficacy (PPE) µmol/J	Improvement in Efficacy %
Title 24 Minimum Efficacy	2.3	Reference condition
Red with Far Red	2.69	17%
RGB with Far Red	3.0	30%
White	3.08	34%
White with Deep Red	3.19	39%
Blue with Deep Red	3.6	57%

Source: DLC. 2024.

Note that 110 of 508—or 22 percent—of fixtures listed on the DLC Qualified Product List as of July 2024 report tested PPE values of 3.5 to 4.1 µmol/J, so substantial savings are feasible with many technology options.

Horticultural lighting systems with spectral tuning capabilities are not yet industry standard practice in California due to low commercial availability and higher associated costs when compared to fixed-spectrum lighting systems, but more manufacturers are now proposing spectral tunable LED fixtures. While there were only 69 spectrally tunable LED horticultural fixtures out of a total 827 listed on the DLC Horticultural Qualified Products List in June 2024, the project team expects that spectrally tunable fixture availability will increase in the coming years, with an associated decrease in cost (DLC 2024).

DAILY LIGHT INTEGRAL (DLI) CONTROLS

CEA crops require sufficient light in each 24-hour period (Hort Americas 2020), which means a daily light integral (DLI) is used to describe the quantity of that light plants receive, whether sunlight or supplemental. DLI is a cumulative calculation of the quantity of PAR light received by plants per area per day—also known as moles per square meter (mol per m^2) per day—from the supplemental lighting systems and natural sunlight in greenhouses. Table 7 below describes the range of suitable DLI for the primary crops within the floriculture, food, and cannabis crop categories.

Table 7: Daily light integral targets for CEA crops.

Crop Category	Crop	Target DLI (mol per m² per day)
Floriculture	Vegetative cuttings (liners)	4 – 10
Floriculture	Seedlings (plugs)	6 – 15
Floriculture	Shade and foliage plants (annuals and perennials)	6 – 10
Floriculture	Potted bulbs	6 – 15
Floriculture	Stock plants for cuttings	10 – 20
Floriculture	Annual bedding plants	10+
Floriculture	Potted flowering plants and herbaceous perennials	12+
Floriculture	Cut flowers	15+
Food	Lettuce	12 – 17
Food	Microgreens	12
Food	Strawberries	17 – 20
Food	Peppers	20 – 30
Food	Cucumbers	15 – 30
Food	Tomatoes	20 – 30
Cannabis	Cannabis (clone/seedling)	15 – 20
Cannabis	Cannabis (vegetative)	20 – 40
Cannabis	Cannabis (flowering)	25 – 50
CEA	**All Crops**	**4 – 50**

Source: Runkle, 2019 (floriculture data), Hort Americas, 2020 (food data), and RII, 2021a (cannabis data).

DLI controls for indoor farms allow for lighting schedules to be manipulated to react to real-time electricity pricing, including peak demand charges. For example, indoor cannabis farms can experiment with providing lower light levels to vegetative plants across longer photoperiods—e.g., 24 hours—to achieve the same DLI as an 18-hour lighting schedule (Agrify 2023). This does not necessarily result in kWh savings, but can save growers money on energy bills and provide resiliency and reliability benefits to the electric grid.

Daylighting is a documented energy-saving benefit for greenhouses using DLI controls, as these controls adjust supplemental lighting levels and photoperiods to achieve a specified DLI given the solar levels achieved throughout the greenhouse. The DLI value is a measure of the total amount of PAR received by plants over a 24-hour period, expressed in moles of photons per square meter per day.

The greenhouse DLI control levels operate as follows:

- **Level 2**: May use light sensors measuring daylight to dim supplemental lighting according to a defined DLI target, which a 2020 New York study demonstrated could result in an energy decrease of 26 percent (NYSERDA 2020).
- **Level 3**: May use light sensors to communicate information with climate control systems, such as lighting schedules and dimming setpoints.
- **Level 4**: May use ML accessing historical solar data to forecast supplemental lighting demand or real-time utility pricing data to plan the timing of energy use for lighting systems to limit peak electric demand (GLASE 2023a).

One example of an emerging Level 4 DLI control system is the Lighting and Shade System Integration (LASSI) program, developed by Cornell University and currently being demonstrated by their Greenhouse Lighting and Systems Engineering consortium (GLASE). LASSI leverages early-day solar insolation data to inform real-time decisions regarding light and greenhouse shade curtain manipulation, ensuring a consistent total DLI of PAR that is conducive to specific plants' optimal growth (GLASE 2020). In a study comparing LASSI performance to a baseline control system—which based output decisions based on PAR threshold control alone—LASSI reduced energy use and energy cost, and delivered a more consistent environment (Harbick et al. 2016).

The LASSI DLI controls energy saving results were highly dependent on crop type and location, and the savings values modeled for them were reported as a percentage decrease of baseline lighting consumption, which can be found below in Table 8. Locations without equivalent California latitude were excluded.

Table 8: Automated greenhouse DLI control energy savings.

Facility Location	California Cities with Equivalent Latitude	Lettuce DLI Control	Tomato DLI Control	Floriculture DLI Control
Elmira, New York	Crescent City, Eureka	24%	20%	28%
Pheonix, Arizona	San Diego, Santa Ana	56%	39%	69%

Source: Harbick et al. 2016.

While the cost of automated greenhouse supplemental lighting systems is an influential factor, the incremental cost of DLI controls can be as small as 2.5 percent compared to the overall price of horticultural lighting and control systems (Microclimates 2024). Investments for Level 3 and Level 4 DLI controls are primarily for software, but despite proven energy and non-energy benefits, Level 4 greenhouse DLI controls like LASSI have not been widely adopted due to high first costs and limited applications in commercial greenhouses in California.

This level of DLI controls requires system integration, as well as potentially more cabling and dimming hardware—if using wired control solutions like 0-10V or Modbus wiring—than basic control (GrowFlux 2023). Growers can use wireless or "semi-wireless" controls to minimize cabling complexity and control up to 12 fixtures with one wireless controller (GrowFlux 2024), and wireless lighting control systems can have different disadvantages than wired systems, like cybersecurity risk potential.

Horticultural HVAC Controls

Horticultural HVAC systems create optimal environments for plant cultivation in controlled environments using specialized HVAC, humidification, and dehumidification systems. These systems are necessary because cultivation of plants introduces three significant cooling loads: sensible load driven by horticultural lighting systems and—for greenhouses—the Sun, and latent load driven by evapotranspiration, or evaporation from floors and benches and transpiration from plants. Transpiration is the movement of water from roots to leaves, where water vapor is released from leaf stomata during photosynthesis—these rates are driven by vapor pressure deficit (VPD), a factor of space temperature and relative humidity.

HVAC system type, fuel source, and efficiency rating all affect the energy consumed by horticultural lighting systems. Electrically driven horticultural HVAC systems are described with different efficiency metrics defined by ASHRAE, including heating seasonal performance factor, cooling system energy efficiency ratio, heat pump system COP, and dehumidification system moisture removal efficiency (RII 2023b). Standard practice for greenhouse and indoor farm HVAC systems varies by facility size and crop type (California Statewide Gas Emerging Technologies Program 2024), and Table 9 summarizes the HVAC technology serving California CEA operations for heating, cooling, and humidity management.

Table 9: HVAC technology serving CEA operations.

CEA Operation Type	Technology Category	Technology Type
Greenhouse	Heating	• Unit heaters • Boilers with hydronic distribution • Infrared heaters
Greenhouse	Cooling and Humidity Management	• Natural ventilation with greenhouse vents • Active ventilation with fans • Evaporative 'pad and fan' cooling systems • Misting/fogging systems • Chillers with hydronic distribution
Indoor Farm	Heating	• Electric Direct Expansion (DX) / heat pump • Boilers with hydronic distribution
Indoor Farm	Cooling and Humidity Management	• Electric Direct Expansion (DX) / heat pump • Integrated HVACD systems • Chillers with hydronic distribution

Source: SCE 2021, California Statewide Gas Emerging Technologies Program 2024.

Title 24, Part 6 of California's energy code currently sets efficiency standards for dehumidification equipment for indoor CEA facilities (CEC 2022), allowing compliance to be reached with one of the four following pathways:

- Dehumidifiers subject to federal appliance standards that comply with the federal performance and testing requirements.
- Integrated HVAC system with on-site heat recovery designed to fulfill at least 75 percent of the annual energy for dehumidification reheat.
- Chilled water system with on-site heat recovery designed to fulfill at least 75 percent of the annual energy for dehumidification reheat.
- Solid or liquid desiccant dehumidification system for system designs that require dewpoint of 50°F or less.

The proposed 2025 version of the code had been considering adding requirements for HVAC environmental controls, but the Final CASE Report did not include this measure (CEC 2024a, 2024b).

Horticultural HVAC controls can reduce CEA facility energy usage by staging and modulating equipment (RII 2021a). The sections below describe the primary energy-saving measures presented by horticultural HVAC controls: automated greenhouse ventilation and vapor pressure deficit reset. Table 10 summarizes the control parameters and units measured by CEA HVAC automation systems.

Table 10: CEA HVAC automation strategies.

Control Strategy	Control Parameter	Unit Measured
Automated Greenhouse Vent Control	Vent Position	% Open
Automated Greenhouse Curtain Control	Solar Radiation Curtain Position	W/m^2 % Open
Automated CEA Fan Control	Fan Speed	% Speed
VPD Optimization	Space Vapor Pressure Deficit	Temperature Relative Humidity

Source: ERI. 2024c.

The following sections describe the energy savings potential of each of the above HVAC control strategies in more detail.

AUTOMATED GREENHOUSE VENT CONTROL

Greenhouses can use gutter vents on roofs or sidewall vents—which can both be automated to open and close depending on actual environmental conditions in the greenhouse—to cool and dehumidify without using energy-intensive equipment. Automated ventilation controllers regulate airflow, temperature, and humidity levels by detecting changes in the controlled environment and actuating vent operation (Goldammer 2021); a recent study found that these systems can reduce cooling energy consumption by 22.6 percent in Italy, which has a Mediterranean climate similar to California (Kaliakatsos et al. 2022). Consumption during the cooling period decreased as the percentage of window opening and duration of the ventilation period both increased. Further details of this observation, along with potential cooling energy savings, can be found in Table 11 below.

Table 11: Automated greenhouse ventilation control energy savings.

Greenhouse Vent Position	Night Only Ventilation	24-Hour Ventilation
Vents Open 50%	15.6%	18.7%
Vents Open 100%	18.7%	22.6%
CEA Average	**17.2%**	**20.7%**

Source: Kaliakatsos et al. 2022.

Automated greenhouse ventilation control levels can work in the following ways:

- **Level 2**: May use environmental sensors measuring temperature and relative humidity to open roof or side wall vents.
- **Level 3**: May use environmental sensors to communicate information with irrigation control systems, such as substrate moisture content.
- **Level 4**: May use ML that accesses historical weather data to forecast ventilation requirements.

AUTOMATED GREENHOUSE CURTAIN CONTROL

Greenhouse curtains—also referred to as shade curtains, energy curtains, or climate screens—shade crops and insulate cultivation environments from solar heat gain during the day and heat loss at night, providing both energy savings and non-energy benefits to growers of diverse crops (GLASE 2024).

Greenhouse curtain monitoring and control systems can detect solar levels, as well as open and close curtains accordingly to optimize heat retention and minimize cold stress on plants. It is key to monitor environmental parameters both above and below the curtain elevation (Hoogendoorn 2024).

Automated greenhouse curtain control levels can work in the following ways:

- **Level 2**: May use environmental sensors measuring temperature and relative humidity to open or close greenhouse curtains.
- **Level 3:** May use environmental sensors to communicate information with lighting or HVAC control systems, such as light levels or space temperature and relative humidity.
- **Level 4**: May use ML accessing historical weather data to forecast curtain system operation.

There is currently minimal literature on the energy saving potential of greenhouse curtain control systems. Table 12 summarizes the modeled monthly reduction in solar radiation, a proxy for cooling energy savings, for single- and triple-screen systems with two different shading percentages for a typical year based on historical weather data. For the single-screen calculation, the curtain is programmed to close when solar radiation levels reach 700 watts per square meter. For the triple-screen calculation, three screens are each set to close, respectively, at 400, 600, and 800 watts per square meter (Svensson Climate Screens 2024).

Table 12: Modeled annual greenhouse curtain control energy savings.

Monthly Reduction in Solar Radiation (J/cm^2)	Single Curtain with 57% Shade	Triple Curtain with 27% Shade
Jan	50%	58%
Feb	51%	59%
Mar	54%	61%
Apr	56%	62%
May	58%	64%
Jun	57%	63%
Jul	53%	62%
Aug	53%	63%
Sep	51%	61%
Oct	47%	58%
Nov	46%	59%
Dec	25%	51%
Annual Greenhouse Average	50%	60%

Source: Svensson Climate Screens. 2024.

As with other systems mentioned in this report, automated greenhouse curtains are not yet industry standard practice in California due to their increased cost and complexity when compared to manual and basic curtain control systems. Additionally, there is a lack of a state energy code requirement for curtains in greenhouses or local policies requiring curtains to reduce light pollution. However, adoption of Level 2, 3, and 4 greenhouse curtain control is more common at large floriculture, vegetable, and cannabis greenhouses like those in Carpinteria, California (GLASE 2024).

AUTOMATED CEA FAN CONTROL

Still air is not desirable in CEA facilities, as air velocities between 0.5 and 0.7 meters per second (m/s) are recommended for plant growth inside greenhouses (Pakari and Ghani 2019). In indoor cannabis cultivation, airflow under the leaf canopy is maintained to 0.5 to 1.0 meters per second to minimize pathogen growth. Air movement through the greenhouse envelope also helps these facilities maintain target environmental conditions, like space temperature.

Greenhouses and indoor farms use two kinds of circulation fans to maintain optimal environmental conditions: Horizontal airflow fans, which move air around the growing area and across the plant canopy, and vertical airflow fans, which move air down from higher elevations in the growing area—like above greenhouse curtains or horticultural lighting—to lower elevations and through the plant canopy.

Automated CEA fan control systems can turn on and modulate fans to maintain a target air speed, the levels of which are described below:

- **Level 2:** May use environmental sensors measuring air speed at elevations of the growing area to modulate fan speed.
- **Level 3**: May use environmental sensors to communicate information with lighting or HVAC control systems, such as lighting or greenhouse curtain operating characteristics.
- **Level 4**: May use predictive algorithms that access historical environmental data from the growing area to forecast fan operation.

A major way automated CEA fan control can save energy is by utilizing a variable frequency drive (VFD) for variable-speed fan control. Table 13 describes the results of a study comparing a manual, or Level 0, greenhouse fan system to an automated Level 2 VFD greenhouse fan system.

Table 13: Variable speed fan control energy savings.

Greenhouse Fan System	Energy Use Reduction %
On-Off Fan Control (Level 0: Manual Control)	Reference condition
Variable Frequency Drive Fan Control (Level 2: Automated Control)	36%

Source: Tietel et al., 2004.

While they are not yet standard practice in California, automated fan systems are more common in larger greenhouses, as the number of fans can be so large the system is not feasible to manually operate.

VAPOR PRESSURE DEFICIT (VPD) OPTIMIZATION

Greenhouses and indoor farms maintain space temperature and relative humidity within target ranges to ensure optimum plant health and vitality (RII 2023b). Vapor pressure deficit (VPD) is a function of environmental conditions, which means the same VPD can be achieved with various temperature and relative humidity setpoints (Schimelpfenig et al. 2020). The VPD value is the deficit or differential between the pressure exerted by the moisture at a specific room condition along with the pressure at saturation, and the surface conditions of plant leaves are assumed to be equal to that of the saturated conditions surrounding them (Desert Aire 2019).

Cannabis can be cultivated under a wide range of setpoints because the plant can tolerate high temperatures, as shown in Figure 10 below. VPD for vegetative cannabis, as shown in green, is typically 0.8 to 0.95 kilopascals (kPa) and VPD for flowering cannabis, shown in yellow, is 0.96 to 1.15 kPa. VPD values higher than 1.15 are generally used to stress plants, which influences various quality factors like yield, color, taste, or aroma.

Temp °F	Relative Humidity													
	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%	40%	35%
87°	0.00	0.22	0.44	0.66	0.88	1.10	1.32	1.54	1.76	1.98	2.19	2.41	2.63	2.85
86°	0.00	0.21	0.42	0.64	0.85	1.06	1.27	1.48	1.70	1.91	2.12	2.33	2.55	2.76
85°	0.00	0.20	0.41	0.61	0.82	1.02	1.23	1.43	1.64	1.84	2.05	2.25	2.46	2.66
84°	0.00	0.20	0.40	0.60	0.80	1.00	1.19	1.39	1.59	1.79	1.99	2.19	2.39	2.59
83°	0.00	0.19	0.38	0.58	0.77	0.96	1.15	1.35	1.54	1.73	1.92	2.12	2.31	2.50
82°	0.00	0.19	0.37	0.56	0.75	0.93	1.12	1.31	1.49	1.68	1.87	2.05	2.24	2.43
81°	0.00	0.18	0.36	0.54	0.72	0.90	1.08	1.26	1.44	1.62	1.80	1.98	2.16	2.34
80°	0.00	0.18	0.35	0.53	0.70	0.88	1.05	1.23	1.40	1.58	1.75	1.93	2.10	2.28
79°	0.00	0.17	0.34	0.51	0.68	0.85	1.01	1.18	1.35	1.52	1.69	1.86	2.03	2.20
78°	0.00	0.16	0.33	0.49	0.66	0.82	0.98	1.15	1.31	1.48	1.64	1.81	1.97	2.13
77°	0.00	0.16	0.32	0.48	0.63	0.79	0.95	1.11	1.27	1.43	1.58	1.74	1.90	2.06
76°	0.00	0.15	0.31	0.46	0.61	0.76	0.92	1.07	1.22	1.38	1.53	1.68	1.83	1.99
75°	0.00	0.15	0.30	0.44	0.59	0.74	0.89	1.04	1.19	1.33	1.48	1.63	1.78	1.93
74°	0.00	0.14	0.29	0.43	0.57	0.71	0.86	1.00	1.14	1.29	1.43	1.57	1.72	1.86
73°	0.00	0.14	0.28	0.42	0.56	0.69	0.83	0.97	1.11	1.25	1.39	1.53	1.67	1.80
72°	0.00	0.13	0.27	0.40	0.54	0.67	0.80	0.94	1.07	1.20	1.34	1.47	1.61	1.75
71°	0.00	0.13	0.26	0.39	0.52	0.65	0.78	0.91	1.04	1.17	1.30	1.43	1.56	1.69
70°	0.00	0.13	0.25	0.38	0.50	0.63	0.75	0.88	1.00	1.13	1.25	1.38	1.50	1.63
69°	0.00	0.12	0.24	0.36	0.49	0.61	0.73	0.85	0.97	1.09	1.21	1.33	1.46	1.58
68°	0.00	0.12	0.23	0.35	0.47	0.58	0.70	0.82	0.94	1.05	1.17	1.29	1.40	1.52
67°	0.00	0.11	0.23	0.34	0.45	0.56	0.68	0.79	0.90	1.01	1.13	1.24	1.35	1.46
66°	0.00	0.11	0.22	0.33	0.44	0.55	0.65	0.76	0.87	0.98	1.09	1.20	1.31	1.42
65°	0.00	0.11	0.21	0.32	0.42	0.53	0.63	0.74	0.84	0.95	1.05	1.16	1.26	1.37

Figure 10: Vapor pressure deficit values for various environmental setpoints, cannabis.

Source: Dr. Greenhouse. 2024.

Leafy greens are less tolerant of high temperatures and prefer VPD values in the 0.8 to 0.95 kPa range, as shown in Figure 11.

Temp °F	Relative Humidity													
	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%	40%	35%
77°	0.00	0.16	0.32	0.48	0.63	0.79	0.95	1.11	1.27	1.43	1.58	1.74	1.90	2.06
76°	0.00	0.15	0.31	0.46	0.61	0.76	0.92	1.07	1.22	1.38	1.53	1.68	1.83	1.99
75°	0.00	0.15	0.30	0.44	0.59	0.74	0.89	1.04	1.19	1.33	1.48	1.63	1.78	1.93
74°	0.00	0.14	0.29	0.43	0.57	0.71	0.86	1.00	1.14	1.29	1.43	1.57	1.72	1.86
73°	0.00	0.14	0.28	0.42	0.56	0.69	0.83	0.97	1.11	1.25	1.39	1.53	1.67	1.80
72°	0.00	0.13	0.27	0.40	0.54	0.67	0.80	0.94	1.07	1.20	1.34	1.47	1.61	1.75
71°	0.00	0.13	0.26	0.39	0.52	0.65	0.78	0.91	1.04	1.17	1.30	1.43	1.56	1.69
70°	0.00	0.13	0.25	0.38	0.50	0.63	0.75	0.88	1.00	1.13	1.25	1.38	1.50	1.63
69°	0.00	0.12	0.24	0.36	0.49	0.61	0.73	0.85	0.97	1.09	1.21	1.33	1.46	1.58
68°	0.00	0.12	0.23	0.35	0.47	0.58	0.70	0.82	0.94	1.05	1.17	1.29	1.40	1.52
67°	0.00	0.11	0.23	0.34	0.45	0.56	0.68	0.79	0.90	1.01	1.13	1.24	1.35	1.46
66°	0.00	0.11	0.22	0.33	0.44	0.55	0.65	0.76	0.87	0.98	1.09	1.20	1.31	1.42
65°	0.00	0.11	0.21	0.32	0.42	0.53	0.63	0.74	0.84	0.95	1.05	1.16	1.26	1.37

Figure 11: Vapor pressure deficit values for various environmental setpoints, leafy greens.

Source: Dr. Greenhouse. 2024a.

VPD optimization can save energy in greenhouses and indoor farms by reducing the amount of cooling and dehumidification required to maintain target space temperature and relative humidity setpoints (RII 2024). Resetting to higher space temperature and relative humidity targets has been estimated to lower demand on cooling equipment by 10 to 40 percent (Surna 2020). Table 14 below describes the energy savings potential of adjusting HVAC system setpoints to achieve the same VPD target of 1.33 kPa.

Table 14: Vapor pressure deficit optimization energy savings.

HVAC Setpoints	VPD (kPa)	Reduction in Cooling Energy Use %
82 °F / 64%	1.34	35 – 50%
80 °F / 62%	1.33	30 – 45%
78 °F / 59%	1.34	25 – 35%
75 °F / 55%	1.33	Reference condition

Source: Surna. 2020.

The Market Characterization of Indoor Agriculture (Non-Cannabis) and Market Characterization of Indoor Cannabis Cultivation studies published by SCE in 2021 described manual controls and simple programmable thermostats as the most common controls system in CEA facilities, with researchers finding that more than 90 percent of growers responding to feedback mechanisms used a human-machine interface to control lighting schedules and HVAC setpoints (SCE 2021, SCE 2021a).

Horticultural Irrigation Controls

Horticultural irrigation systems create optimal environments for indoor plant cultivation using specialized watering systems to support optimal plant transpiration. Irrigation activities create interactive effects, with watering events influencing plant transpiration rates and affecting VPD in cultivation spaces. The traditional control strategy for irrigation is manual watering via hoses, but some growers also use timeclock automation, where a grower programs an on/off cycle schedule to distribute water to substrate for a set period. While this system may save labor, it often results in increased water waste due to overwatering during darker periods, as plants transpire less when the sun is down or the lights are off.

Horticultural lighting systems' energy consumption is driven by irrigation practices. Micro-irrigation, which can be automated, uses drip or trickle irrigation and micro-sprinkler technology for plant watering and fertigation—the addition of nutrients to irrigation water (Harrison 2022). Micro-irrigation is considerably more resource-efficient for both water and energy; it reduces the frequency and volume of watering events and distributes water to substrate for watering events based on soil moisture content.

Table 15 summarizes the control parameters and units measured by CEA irrigation automation systems.

Table 15: CEA irrigation automation strategies.

Control Strategy	Control Parameter	Unit Measured
Variable-Speed Pump Control	Pump Speed	% Speed
Sensor-Based Irrigation Controls	Watering event start/stop Watering event frequency Watering rate	Time of day Substrate moisture content Plant weight

Source: ERI. 2024c.

The following sections describe the energy savings potential of each of the above irrigation control strategies in more detail.

VARIABLE-SPEED PUMP CONTROL

Because CEA facilities require consistent delivery of water to plants as crops grow and develop, irrigation pump skids can incorporate single-speed pumps for constant flow or variable speed drives (VSD) to modulate pump speed according to demand and reduce energy use.

There are no recent studies of energy savings from VSD irrigation for CEA irrigation applications, but Table 16 below describes the potential energy savings of variable speed pump control for irrigation applications.

Table 16: Variable speed pump control energy savings.

Irrigation System	Energy Use Reduction %
Constant Speed Pump Control	Reference condition
Variable Frequency Drive Pump Control	27 – 35%

Source: Lamaddalena and Khila. 2011.

As with other technologies mentioned throughout the report, VSD pumps are not yet California CEA industry standard practice but are more common in larger operations, one example of which can be found in the irrigation section of the Greenhouse #3 Site Visit Report.

SENSOR-BASED IRRIGATION CONTROL

To mitigate water and energy waste and improve precision, timeclock irrigation systems can integrate sensors to monitor environmental conditions. This approach allows the timeclock to determine irrigation schedules based upon accumulated light exposure or plant parameters, such as substrate moisture content, leaf canopy temperature, or root zone electrical conductivity (EC). By tailoring irrigation cycles to real-time conditions, growers can optimize water usage while minimizing energy use and nutrient runoff. Sensor-based micro-irrigation systems can use 33 to 50 percent less water than sprinkler irrigation systems, which can decrease energy consumption while providing non-energy benefits like reduced weed growth.

Three examples of sensor-based irrigation control are described below:

- **Volumetric water content (VWC) control.** VWC sensors measure soil moisture to control irrigation events and consist of multiple rods or waveguides that analyze the waveform of an electromagnetic pulse through the substrate. The sensors can also measure root temperature and EC, which can integrate with control systems to notify timeclock systems when plants demand more water. While the sensors provide direct feedback, they must be calibrated to each substrate type, and monitored plants must be representative of the entire crop.
- **Evapotranspiration (ET) control.** ET occurs through two pathways: transpiration through a plant's leaf pores and evaporation through the root substrate. Within ET control, sensors collect accumulated light exposure measurements to inform automated irrigation systems, as 80 to 90 percent of water uptake is driven by the amount of light received over time. This control method is especially effective at reducing excess irrigation during low-light level conditions and has high integration potential for CEA facilities that use supplemental lighting

controls. The principal drawback of accumulated light exposure measurement systems is that they require large amounts of input data. ET modelling means growers must invest in high-computing capacity at a higher cost, as the control requires sensor inputs of light, temperature, airflow, and VPD, and may also incorporate leaf temperature and substrate VWC variables (DoI 2020).

- **Gravimetric control.** Automated irrigation systems use scales that monitor changes in plant weight within a representative section of the crops to analyze transpiration rate, which then informs decision-making systems that automate irrigation frequency and duration. This strategy reduces fluctuations in soil moisture content and nutrient density, in turn reducing plant stress. However, if plants within the crop are variable, the representative segment of plants is inaccurate and leads to poor system performance (RII 2023c).

Water use can decrease when using two environmentally responsive, sensor-based measurement methods instead of depending on timeclock control (Nikolaou et al. 2019). Energy savings from sensor-based irrigation controls are behavioral and dependent on the facility type and crop type, which influences watering demand, as summarized further in Table 17 below.

Table 17: Sensor-based irrigation control energy savings.

Irrigation Control Strategy	Energy Use Reduction %
Timeclock control	Reference condition
Sensor-based control	33 – 50%

Source: Nikolaou et al. 2019.

For an example of how sensor-based irrigation systems are used in larger California CEA operations, please see the irrigation section of the Greenhouse #3 Site Visit Report.

Energy Efficiency (EE) Program Landscape

As the energy efficiency program landscape expands, so do incentives for greenhouse controls. Since 2019, Efficiency Vermont has offered a greenhouse controller rebate of $0.10 per square foot (Efficiency Vermont 2024), while DTE in Michigan offers $0.05 per square foot for greenhouse environmental controls and requires projects implement automated setbacks of at least 5°F (DTE 2024).

Additionally, some US utilities offer CEA lighting controls rebates, such as Commonwealth Edison's incentive for LED Grow Networked Lighting Control Systems in Illinois (Commonwealth Edison 2024). Horticultural lighting control systems can receive $0.40 per watt if the system meets the following requirements:

- System must have a graphical user interface that is accessible from a single central computer and/or mobile device without the need to move around to access separate fixtures.
- System must have network interoperability, e.g., BACNet MS/TP, Zigbee, etc.
- System must have the ability to show the "real-time" status of the light fixtures, e.g., on/off, dimmed, etc.
- All installed sensors must be tied to the central control system.
- The following control strategies must be implemented to qualify:
    - **Scheduling:** Automatically affects the operation of lighting equipment based on time of day.
    - **Continuous dimming:** Provide control with sufficient resolution in output—100-plus steps—to support light level changes that are perceived as smooth.
    - **Zone control**: Group luminaires and form unique lighting control zones for a control strategy via software-defined means, and not via physical configuration of mechanical or electrical installation details.
    - **Humidity control:** Monitor and automatically modify the relative humidity in the grow space to specified conditions.
    - **Temperature control**: Monitor and automatically adjust the temperature within a specified range.
    - **CO_2 sensing**: Monitor and control CO_2 concentrations in the illuminated grow space.

Utilities in Canada offer increased incentives--$350 per fixture versus $250 per fixture—for LED horticultural light fixtures if they are connected to automated control systems (Save on Energy 2024).

Objectives

This section describes the diverse approaches the team took during the market assessment for stakeholder outreach and engagement.

This phase of the project examined new measures for emerging technology that may remove barriers and improve market penetration. To characterize the state of the CEA market in California, the project team conducted surveys, interviews, and site visits to gain insight from various stakeholders across the greenhouse and indoor farming markets. The team then analyzed the data to determine the energy savings over the incumbent technology. The Recommendations section of this breaks down the impact of and provides further detail on these market assessment approaches.

Customer Surveys

The team gathered information about customers' installed controls systems and implemented EE measures, and collected data regarding type of facility, whether greenhouse or indoor; size of facility; and facility crops, including food, floriculture, and cannabis.

Stakeholder Interviews

These insights from industry subject matter experts, who work closely with CEA growers and their facilities in California, helped the project team corroborate insights from customer surveys and site visits. The interviews also collected additional data on emerging technologies, their applications, and recommended measure approaches.

Customer Site Visits

Customer site visits offered insights from the field and documented lighting, HVAC, irrigation, and control system characteristics. Site visits also helped identify EE opportunities, collect information about the level of adoption of emerging technology, and understand CEA-specific barriers to implementing EE projects.

Methodology and Approach

This section summarizes the outcomes of the market assessment's stakeholder outreach and engagement activities.

Table 18 below summarizes the results of the assessments, which exceeded or achieved target response rates for surveys, interviews, and site visits. The project's research team surveyed 19 growers, interviewed 18 CEA industry stakeholders, and visited four CEA facilities between March and April 2024.

Table 18: Stakeholder engagement summary.

Stakeholder Engagement Instrument Outreach Mechanism	Target	Individuals Contacted	Respondents	Target Achieved	Response Rate
Surveys	800 – 1,000	1,175	19	Exceeded	1.6%
Interviews	10	31	18	Exceeded	58%
Site Visits	4	1,175	4	Achieved	0.3%

Source: ERI. 2024.

Market Assessment Findings

The sections below provide detailed insights from the market assessment's surveys, interviews, and site visits.

A portion of interview and site visit participants provided energy data for analysis, and one investor-owned utility provided anonymized monthly electricity usage data for analysis. Refer to the Energy Analysis section of this report for further insights from monthly utility data.

Survey Results

Figure 12 through Figure 17 below illustrate collected data for survey respondents (ERI 2024a), including input from 19 CEA growers, which was shared between January and May 2024. Appendix B includes the questionnaire provided to survey respondents.

Survey respondents represented CEA facilities in diverse climates throughout California—including Humboldt County, Central Coast, Sacramento Valley, and the Mojave Desert—and spanned Survey respondents represent 12 out of the 16 California CZ, with the following CZ's represented: CZ01, CZ02, CZ03, CZ04, CZ05, CZ06, CZ07, CZ08, CZ09, CZ11, CZ12, CZ13. The oldest surveyed facility was built in 1978, though most respondents' facilities are much newer, with a median age of five years. Two respondents did not fully complete the survey, and two responses represent different facilities operated by the same company, which use very similar equipment and controls strategies.

Survey responses cover a wide range of facility sizes that ranged from 15,000 to 870,000 square feet, with an average facility size of 259,000 square feet and a median facility size of 65,520 square feet. This was influenced by the wide split between smaller and larger facilities—36 percent of facilities were less than 100,000 square feet, while 21 percent were greater than 500,000 square feet.

Survey respondents were primarily greenhouse operators, as illustrated in Figure 12 below. 18 percent of respondents operated indoor farms, and one in three indoor farm respondents grew their crops in vertical racks.

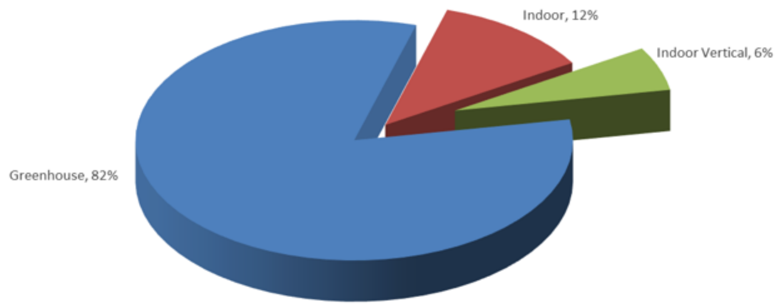

Figure 12: Survey participants by CEA facility type.

Source: ERI. 2024a.

While survey respondents grew all the primary CEA crops of food, floriculture, and cannabis, Figure 13 below shows that 82 percent of respondents grew non-cannabis crops.

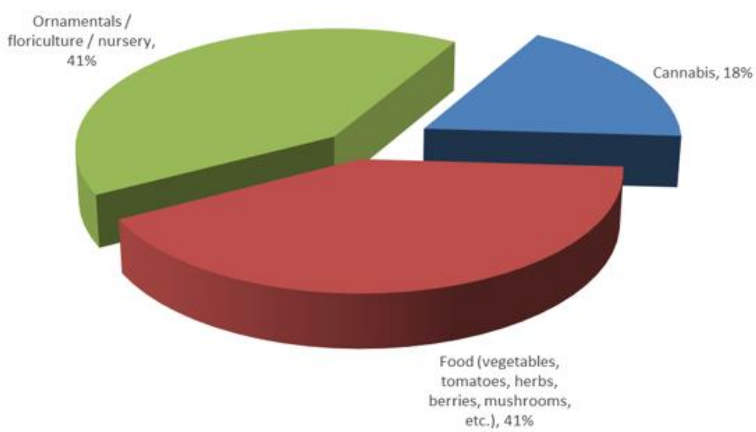

Figure 13. Survey participants by crop grown.

Source: ERI. 2024a.

When considering EE upgrades, Figure 14 shows that 33 percent of surveyed growers were concerned with first cost and 40 percent were concerned with system performance, although responses were not mutually exclusive. By contrast, only 13 percent of growers indicated that they were concerned with additional training requirements, and 0 percent of growers indicated concern with labor availability.

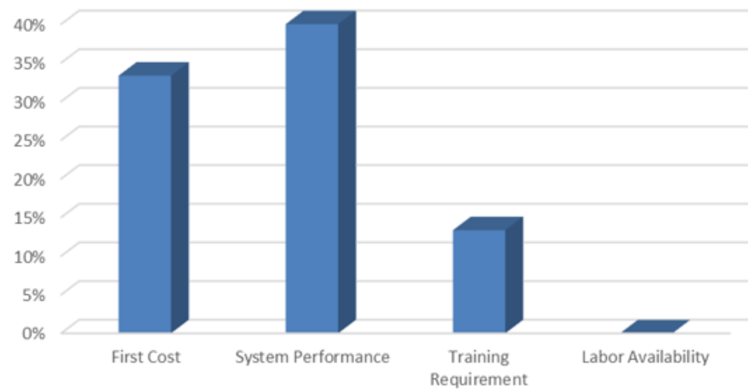

Figure 14: Grower concerns with energy efficiency.

Source: ERI. 2024a.

Growers desired short financial paybacks on EE projects, as illustrated in Figure 15. 87.5 percent of growers wanted efficiency projects to pay back within five years, while 37.5 percent of growers hoped for paybacks shorter than two years.

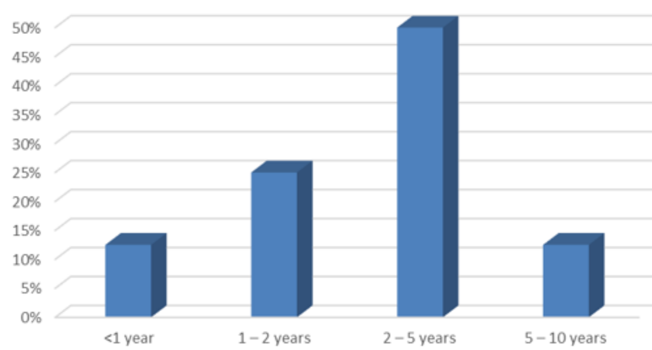

Figure 15. Desired payback for energy efficiency projects.

Source: ERI. 2024a.

Figure 16 shows the level of control used by respondents for the three major CEA process systems of lighting, HVAC, and irrigation, with N/A responses explained below. Level 0 manual control was the most common for irrigation control applications, while Level 1 basic control was more often used for HVAC and irrigation systems. Forty-five percent of respondents used single-speed ventilation fans, and 27 percent of respondents did not use horticultural lighting systems. When growers use lighting systems, they are likely to employ integrated or intelligent automated controls for lighting; 64 percent of growers using horticultural lighting reported using Level 3 or Level 4 controls. Most respondents reported using integrated or intelligent automated controls for HVAC systems, and 53 percent of surveyed growers used Level 3 or Level 4 controls for HVAC systems. Finally, while 40 percent of respondents used Level 2 automated irrigation systems, only 27 percent used Level 3 integrated or Level 4 intelligent irrigation control systems.

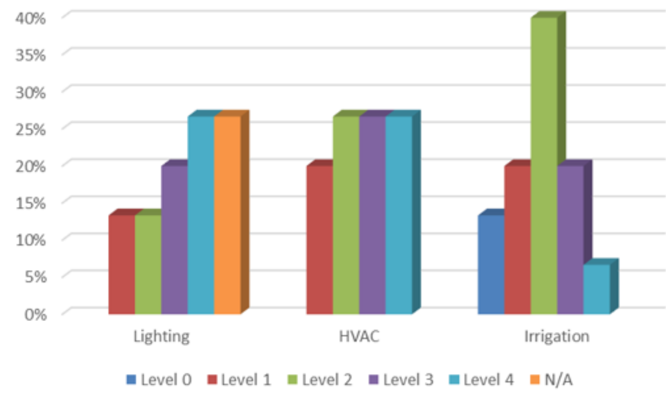

Figure 16. Level of automation by system.

Source: ERI. 2024a.

Figure 17 reports the highest level of automation for all process systems by facility crop type and shows that facilities growing food were more likely to have the highest level of automation—Level 4 control—for at least one major system. Meanwhile, floriculture growers were more likely to use Level 3 control integrated systems, and only 13 percent of respondents used Level 1 basic control systems. No respondents used Level 0 manual control as their highest level of control.

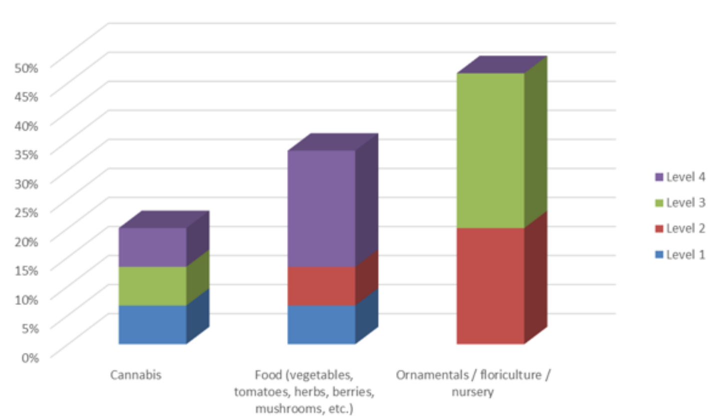

Figure 17: Highest level of automation by crop type.

Source: ERI. 2024a.

Since 50 percent of survey respondents operated facilities larger than 100,000 square feet, it is important to examine the level of automation by facility size. Figure 18 shows that facilities smaller than 100,000 square feet were more likely to use Level 2 standalone automation systems, while facilities larger than 100,000 square feet were more likely to use Level 3 integrated automation systems, and also more commonly reported Level 4 intelligent control systems. Overall, large facilities exclusively used Level 2 or higher controls, with 88 percent of respondents who operated large facilities reporting using Level 3 or Level 4 controls.

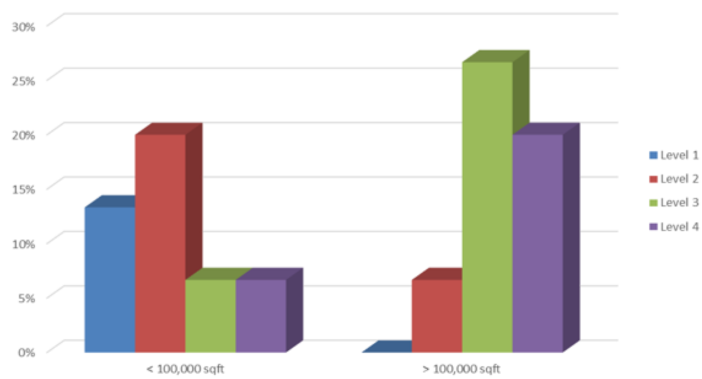

Figure 18: Level of automation by facility size.

Source: ERI. 2024a.

Figure 19 below illustrates the level of energy monitoring respondents reported based on their level of controls integration. Respondents operating facilities with Level 4 intelligent control systems were the only respondents monitoring their energy use at the system level. Facilities using Level 3 integrated control were more likely to be monitoring energy use at the facility level.

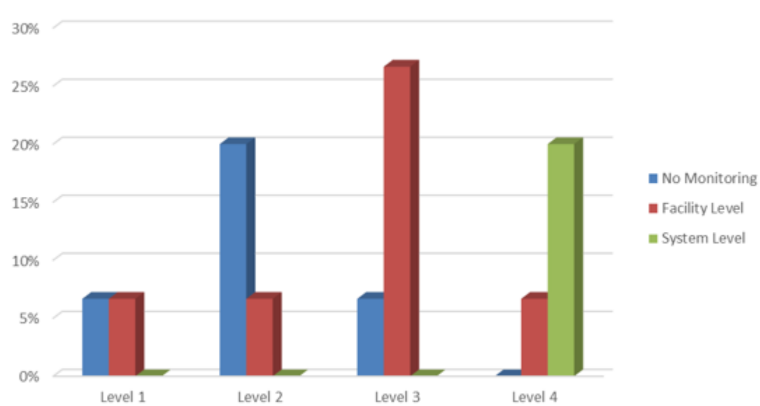

Figure 19: Facility energy monitoring by highest level of automation.

Source: ERI. 2024a.

Interview Findings

Conversations with industry subject matter experts complemented findings from grower surveys, although they do not completely align.[1]

The research team interviewed equipment vendors and industry organizations to understand emerging technologies and new products. Additionally, we interviewed some growers to gather opinions on the level of adoption of smart CEA environmental controls, qualitative feedback on system performance of smart environmental controls systems, and their experience with efficiency program participation.

This section anonymizes interviewee affiliation by using industry segment and a unique letter to identify each subject matter expert, as described in Table 19 below. The input from these 18 interviewees is representative of the key stakeholders transforming the CEA market.

Table 19: Site visit summary.

Stakeholder Type	Location	Number of Stakeholders	Stakeholder IDs
Greenhouse Growers	California	4	California Grower A California Grower B California Grower C California Grower D
Indoor Farmers	US	1	Grower D
Academic Researchers	US	3	Researcher A Researcher B Researcher C
Equipment Manufacturers	Global with projects in California	5	Manufacturer A Manufacturer B Manufacturer C Manufacturer D Manufacturer E
EE Program Implementers	California	1	California EE Program Implementer A

[1] This discrepancy can be partially explained by the high representation of large facilities in survey responses. Large facilities use larger and more complex horticultural lighting, HVAC, irrigation systems, which require more automated and integrated controls. Another potential contributing factor is that growers employing automated, integrated, and intelligent controls are likely to be more tech-savvy than growers with manual or basic control systems and are therefore more likely to respond to email and phone outreach or an online survey.

Stakeholder Type	Location	Number of Stakeholders	Stakeholder IDs
Energy Code Expert	California	1	California Energy Code Expert A
Professional Association	US	1	Professional Association A
Industry Organization	US	1	Industry Organization A
Controls Certification Program	North America	1	Controls Certification Program A

Source: ERI. 2024b.

Automated Control System Commentary

California Grower A works with an integrated control system for lighting and HVAC systems like dehumidification, humidification, under-bench heating, and airflow equipment, but uses basic controls, such as an outdoor light sensor, for their greenhouse curtains. They use mostly manual controls, e.g., hoses or drip irrigation, for their irrigation systems.

Academics often work with CEA companies and build their own horticultural research laboratories on campus. Researcher A, who is not located in California, shared that automation is popular because it reduces demand for labor and some growers use it for commercial marketing purposes. Researcher B, who is located in a California IOU territory, said that cannabis cultivators more often use manual or basic controls, and has also found that cannabis growers are more open to collaboration but are difficult to reach. The market of California CEA operations that grow food is still very small, according to Researcher B, who also feels they are challenging to collaborate with. “They do not allow for any demonstration projects unless you have very good connections,” Researcher B said. This researcher also told the team that the California greenhouses collaborating with their university “do not care about precision control” and that it is “difficult to motivate them to adopt automation.”

Researcher C, who is not located in California, conducts experiments with automation and uses DLI controls but does not monitor energy use for their studies. At their university, controls have not been upgraded since 2016 due to the high capital cost.

Professional associations that create standards affecting the CEA industry are currently gathering input on the requirements that may be added to the next versions of the standard energy code, which is used throughout the United States, including in California. For now, requirements suggested by Professional Association A’s working groups address equipment efficiencies, though this professional association shared that there is not much information on controls in existing regulations.

Industry organizations focused on resource efficiency have published best practices guidance for CEA automation and controls. Industry Organization A shared that their 20-person working group seeks to explain how CEA control systems work while recommending ways to reduce energy and water use—including strategies like advanced greenhouse daylighting control and indoor farm VPD control. The organization is partnered with a national lab to accelerate EE in the CEA industry, as they believe academic research is crucial for validating claims from manufacturers.

California EE Program Implementer A said that a deemed measure for CEA system automation and integration would be more successful than a custom measure, which they explained is due to the 85 percent decline in custom projects in the past five years. "Retro-commissioning measures with a deemed pathway would be nice," the implementer said. From California EE Program Implementer A's experience working with California farms, the smaller the greenhouse, the lower the level of controls system sophistication. For example, smaller greenhouses manually open and close shade curtains.

Integrated and Intelligent Control System Commentary

Proper integration of CEA controls can be difficult. California Growers A, B, and C all use commercially available integrated control systems in their greenhouses. California Grower D, who operates an indoor farm, claims to have "designed and constructed the most sustainable and automated farm ever built" and uses predictive control to maximize EE and dispatch on-site renewable energy sources and battery storage systems. Grower E, who is not located in California, said that they built their own integrated and intelligent controls system in-house for their indoor farm rather than buying one off the shelf.

Some manufacturers have been selling integrated and intelligent controls systems for 25 years across the globe. Manufacturer A notes that few high-tech growers in the United States have a rich energy management data history. Their research team in the Netherlands is building a digital twin of energy systems to use AI and proactively switch from natural gas to electricity using advanced controls and combined heat and power systems.

System integrators working in California shared that funding for automation is challenging and much harder for cannabis cultivators than food producers. Manufacturer B described the challenges a cannabis grower experienced on a California Native American reservation, which is considered a disadvantaged community (DAC). The grower had Level 0 manual controls for every horticultural process system, with one employee dedicated to operating every on/off switch. Since cannabis cultivators make up 34 percent of the growers in California, is important for IOUs to offer generous incentives that substantially reduce the capital costs for automating CEA environmental controls; utility rebates may be the only source of external funding these customers can leverage for energy efficiency projects.

Manufacturer B also stressed the importance of heterogeneous data, explaining:

> "Data from various sources are needed to teach machine learning (ML) models—otherwise, AI can hallucinate. ML and AI systems need diverse and extensive data to avoid overfitting, bias, and hallucinations. Heterogeneous data ensures models learn generalizable patterns and represent various groups accurately. Extensive data enhances accuracy and robustness, helping AI systems understand context correctly and reduce errors. Diverse, large datasets are crucial for reliable and effective ML and AI systems."

Growers and utilities alike can benefit from a common analysis platform for accessing and analyzing plant, weather, and energy data. Manufacturer B categorized CEA controls manufacturers into hardware manufacturers, who sell black box products, and system integrators, who are more open and flexible with data-sharing across software platforms.

Energy Monitoring Commentary

Researcher B, who runs a program based at a state university that helps California producers with energy audits and identification of system optimization opportunities, said that most California CEA growers do not track energy use, and those who do are reluctant to share data—and some do not know the data even exists. For example, California Grower A did not know that their system could report energy use at the time of the interview, but later learned the functionality just needed to be turned on. This grower is now gathering energy use data to observe trends. California Grower B said that they “don’t really look at the energy monitoring data at the system level” for lighting or HVAC systems that is provided by their Level 4 integrated and intelligent control system.

California Grower C’s facility does not use energy monitoring, but the grower now wants to implement it so they can understand energy use at the system level and manage electricity bills. California Grower D monitors energy at the system level using smart meters, but tracks this separately from the automation system; they shared that greenhouses often track energy use at the facility level, as it is a key metric affecting profitability. Finally, Grower E—who is not located in California—shared that CEA energy use is like “standing on top of a hill on a windy day and ripping up $50 bills.”

Standardized energy reporting is also crucial. Manufacturer B shared that companies need to describe how they are generating energy data so users can distinguish the quality of data. Energy monitoring data can be calculated or can be reported from energy monitoring hardware installed at the circuit level.

California EE Program Implementer A described cannabis growers as having the largest energy monitoring gap, with only two growers the implementer personally knows of using energy monitoring data. The implementer also said they are not sure any California grower they work with could give them “a firm kilowatt-hour per square foot or pound,” despite Dutch growers commonly knowing these metrics.

Horticultural Lighting Control System Commentary

Lighting controls in California CEA facilities vary by crop type. For example, California Grower A grows floriculture crops and uses horticultural lighting systems, but they are not dimmable. Meanwhile, California Grower B said that their flowering cannabis greenhouses use supplemental lighting to ensure a DLI of 30 to 35 moles per square meter per day. If sunlight levels exceed 500 watts per square meter, supplemental lighting systems are turned off. Grower B uses shade curtains to reduce light levels in summer, which keeps consistent yields throughout the year.

Lighting controls manufacturers have been developing horticultural lighting products, as well as scheduling and controlling equipment wattage and spectral treatment, to manage loads, reduce energy use, and attain non-energy benefits for plant growth and development. Some are physically testing light fixtures themselves and measuring and tracking spectral data. Manufacturer C shared that while California growers “tend to be on board with monitoring energy use,” in 2024, most growers they worked with controlled lighting, HVAC, and irrigation systems separately.

Even if systems are integrated, Manufacturer B noted that “contactor panels are the baseline,” with cabling run to every light and panel. Manufacturer D offers dynamically controlled LED light fixtures and controls with real-time rectification of PPFD and spectral treatment. Some strategies offered by Manufacturer D include DLI rollover—e.g., 5 moles per square meter of light from sunny days can roll over to cloudy days—and spectral tuning. Manufacturer D characterizes light fixtures and calculates the energy consumed by lighting systems in the field, as energy is not actually monitored at each site. Lettuce growers are the CEA operators who benefit most from lighting system automation, DLI control, and spectrum control because researchers and commercial growers have both observed quality and growth characteristics of leafy greens improve with dynamic light treatments.

The 2022 version of California Energy Code, Title 24, Part 6 for controlled environment horticulture (CEH) requires time-switch/timeclock controls and multilevel/switched dimming controls for greenhouses and indoor growing lighting systems with more than 40 kilowatts of connected horticultural lighting load. While the 2025 version of Title 24, Part 6 for CEH increased efficacy requirements for lighting systems, it offers no significant changes to lighting controls measures, although proposed changes to the 2028 energy code began undergoing consideration in 2024 (CEC 2024d).

California Energy Code Expert A said that utility EE programs help increase market adoption and suggested that a successful program be run before Title 24 codifies horticultural lighting controls, emphasizing the need for outreach and education with incentives. They also shared that the greatest energy savings opportunity for California CEH is adaptive daylighting controls for greenhouses and that the measure has defensible savings if algorithms and data are used to verify actual lowered energy use.

Lighting controls certification programs that work with utilities recommend supporting listed controls products for incentive programs. Third-party Controls Certification Program A said utilities need to provide support like incentives for growers to overcome first-cost barriers for advanced lighting controls, as California growers primarily use Level 0 manual or Level 1 basic controls. Like other subject-matter experts in these interviews, they described energy monitoring as “not terribly common,” and said energy savings from controls measures like spectral tuning and system integration are considered promising.

Horticultural HVAC Control System Commentary

HVAC controls across California CEA facilities are also crop-dependent. California Grower A, who grows floriculture crops, said all their cooling fans used VSDs, which control HVAC systems to a “ventilation requirement” based on greenhouse temperature and relative humidity. Equipment is phased in, with roof vents opening incrementally while fans are ramped up in stages. In Grower A’s propagation areas, their integrated control system maintains a target VPD range for unrooted cuttings.

California Grower B, who cultivates cannabis, said air movement is “very important” to them and described a planned installation of thousands of horizontal airflow fans across their 100 acres of greenhouse facilities. They have two semi-closed greenhouses, with more active cooling systems like an evaporative pad and fan “wet walls.” California Grower C, who grows lettuce, operates two greenhouses that use integrated HVAC controls, although one has active cooling systems and the other has almost no space conditioning.

Manufacturers note that the complexity of CEA HVAC systems necessitates automation. Manufacturer E shared that while heating systems can handle simple controls, cooling and dehumidification systems cannot, and more sophisticated automation systems are needed to control all the different modes. Smaller greenhouses may use manual shutoff valves for heating each bench, but the larger the greenhouse, the more time consuming it is to shut valves off manually. Facilities greater than 10,000 square feet are more likely to zone their HVAC systems and use more automation. This can be a costly endeavor, as Manufacturer E noted that HVAC and climate control systems can be more expensive than the facilities that house them—for example, up to $10 million, compared to $4 million for constructing the greenhouse itself. The same manufacturer told the research team that California cannabis, vegetable, herb, and strawberry growers are more likely to use automated controls than floriculture due to higher profit margins and cultivar-specific environmental requirements.

Manufacturer F's climate control software uses both machine learning and more conventional programming algorithms, incorporating Dutch plant empowerment principles to optimize plant conditions for the highest production efficiency.

"Efficiency of resources is key," Manufacturer F said. "We can all produce a certain number of kilograms, but we make it possible with less energy, CO_2, water, and fertilizers."

Additionally, the manufacturer said California floriculture and tomato growers are benefiting from adopting smart environmental controls like Manufacturer F's system, which uses inputs from infrared cameras to calculate leaf temperature and track actual VPD in cultivation spaces. The system can analyze video feeds for plant growth and crop health to inform the decision-making model. Manufacturer F's system monitors energy at the system level but they say it has been challenging for their customers to get utility incentives for the technology.

Horticultural Irrigation Control System Commentary

Methods for controlling watering events in California CEA facilities also vary by crop type. California Grower B said cannabis is a crop that growers "need to know when not to water; it is better to hold a shot than to give it." Their facility uses gravimetric grow scales and moisture content meters to monitor a sample of plants in real time, which allows them to observe the moment when plants start drinking. The grower uses predictive information on substrate to determine if, and how much, irrigation is necessary for every watering event throughout the day, as well as to assess what nutrients are needed, if any. California Grower C growing lettuce has one greenhouse using Deep Water Culture and one using a pond system for irrigation; pumps run 24/7 to recirculate water and are operated manually (plants are also watered manually).

Site Visit Results

Site visits and discussions with facility managers at four CEA facilities in California complemented findings from customer surveys and industry stakeholder interviews, and allowed the research team to observe equipment and systems in four different California CZ. The average facility size was 1,224,950 square feet and the median size was 43,900 square feet; the difference between the average and the median is due to the large size of one of the visited facilities, which grows in 110 acres of greenhouses, or approximately 4.8 million square feet. Table 20 describes the four CEA facilities visited in January to March 2024, along with the level of automation for each major horticultural process system.

Table 20: Site visit summary.

CEA Facility ID	Location	Crop Type	HVAC Equipment & Controls	Lighting Equipment & Controls	Irrigation Equipment & Controls
Indoor Grower #1		Cannabis	Level 1	Level 0	Level 2
Greenhouse #1	CZ14	Cannabis	Level 4	Level 4	Level 4
Greenhouse #2	CZ05	Cannabis, Cucumbers, Tomatoes	Level 4	Level 2	Level 4
Greenhouse #3	CZ03	Roses, Strawberries	Level 2	Level 2	Level 2

Note: Refer to Appendix C: Site Visit Reports to read detailed site visit reports for each facility.
Source: ERI. 2024e.

Site Visit Findings

The team's site visits yielded results with higher levels of controls automation than other feedback mechanisms in this report.

50 percent of the facilities used Level 4 controls for multiple systems, including irrigation, which contrasted with the survey and interview findings. The survey findings indicated that Level 2 controls were most common for irrigation, with higher levels of control being more common for lighting and HVAC systems. Meanwhile, the interview findings indicated that Level 0 and Level 1 controls were the most common for all greenhouse systems throughout California.

The sites the research team visited may be less representative of the California CEA market. Greenhouse #2 is a large 110-acre greenhouse facility, and due to its size and complexity, uses advanced and automated controls by necessity. Greenhouse #1 is smaller but was designed from the ground up as a testbed for highly automated, off-grid CEA.

Energy Analysis

To characterize the California CEA market and understand the energy savings potential of smart environmental controls for horticultural process systems, it is useful to benchmark electric energy use intensity (EUI). However, the size of a CEA facility may not always be known, so other metrics can be used to benchmark energy use over time. The Site-Level Energy Analysis section of this report provides more detail on electric EUI by California CZ.

During the market assessment phase of the project, several survey and site visit participants voluntarily provided energy data for analysis for months in 2022 through 2024.

Additionally, the Loadshape Analysis section of this report describes loadshapes for CEA facilities using anonymized electricity consumption data from 66 CEA facilities provided by PG&E for ranges of months from 2021 to 2023.

Site-Level Energy Analysis

The team used data from 2022 and 2023 to create a 12-month loadshape for each of the three CEA operations that shared electricity consumption and demand data. Table 21 summarizes the facility details of and provides the calculated electric EUI for each CEA operation.

Table 21: Site-level energy analysis summary.

Energy Analysis ID	California Climate Zone (CZ)	Crop Type	Facility Size (ft^2)	Annual kWh	Electric EUI (kWh/ft^2)
Indoor Farm A	CZ12	Cannabis	22,800	3,677,461	161.29
Greenhouse A	CZ12	Floriculture (Orchids)	65,520	574,852	8.77
Greenhouse B	CZ05	Cannabis, Cucumbers, Tomatoes	4,800,000	11,886,303	2.48

Source: ERI. 2024d.

Based on the analysis of this sample of facilities, indoor farm electric EUI is heavily influenced by crop type and can be 29 times higher than greenhouse electric EUI. The data illustrates the vast discrepancy in energy use between indoor and greenhouse facilities—for example, Indoor Farm A's electric EUI is 18 times greater than Greenhouse A, though they are both in the same CZ. This order-of-magnitude difference in electric EUI is primarily driven by the use of sole-source horticultural lighting in indoor farms, as well as the more energy-intensive mechanical cooling technologies, compared to the use of supplemental lighting systems and less energy-intensive, passive HVAC systems in greenhouses. However, the differences in electric EUI may also be attributable to other factors, such as CZ, crop requirements, and level of controls system automation.

The following sections describe each farm's energy analysis, including monthly load profiles and peak demand where available.

Indoor Farm A

Indoor Farm A is a 22,800-square-foot indoor cannabis growing facility, located in Sacramento, California within CZ 12. The indoor facility is fully enclosed and insulated, and as a result, internal loads of the plants and lighting are more dominant than external loads, resulting in relatively flat usage throughout the year, as shown in Figure 20 below. Indoor Farm A has an average monthly electricity consumption of 369,200 kWh and peak demand of 979 kW.

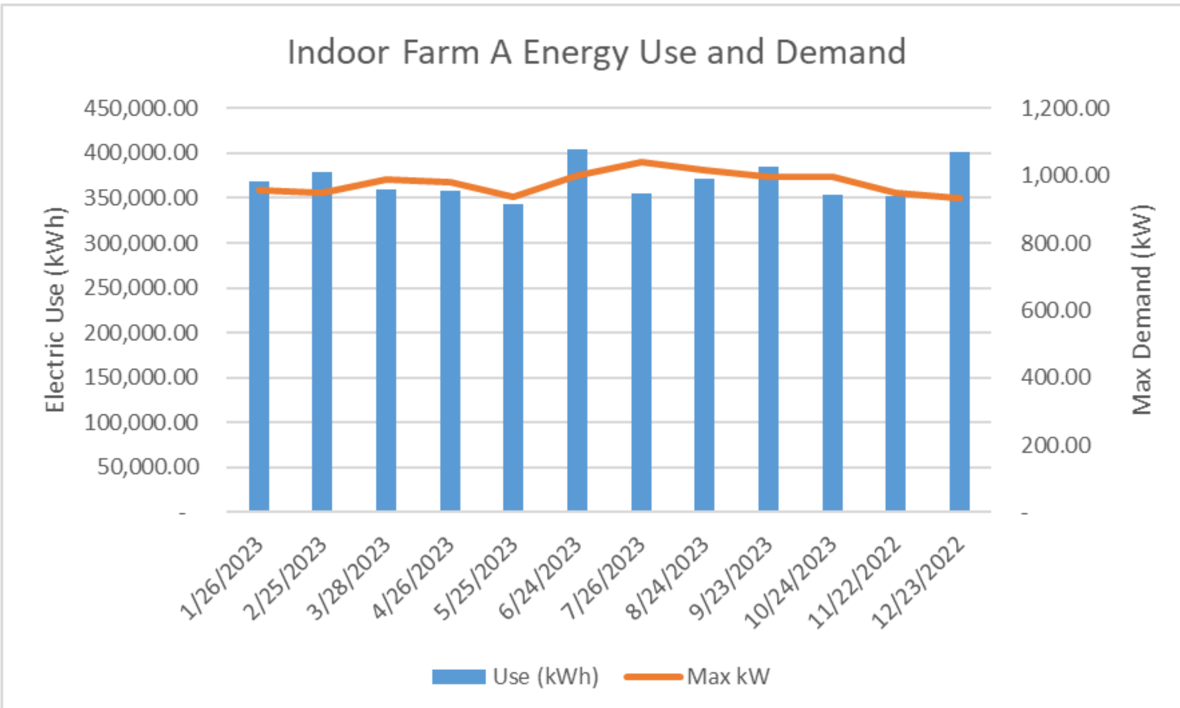

Figure 20: Indoor Farm A monthly electricity use and demand.

Source: ERI. 2024d.

Greenhouse A

Greenhouse A is a 65,520-square-foot greenhouse facility that primarily grows orchids, located in Lodi, California in CZ 12. Greenhouse A exhibits expected energy usage patterns, with electricity use primarily driven by cooling. As shown in Figure 21, energy use increases through the spring as weather conditions warm and reaches a maximum in July and August when cooling loads are highest, with average electricity consumption at 47,900 kWh per month. Demand data was not available for Greenhouse A.

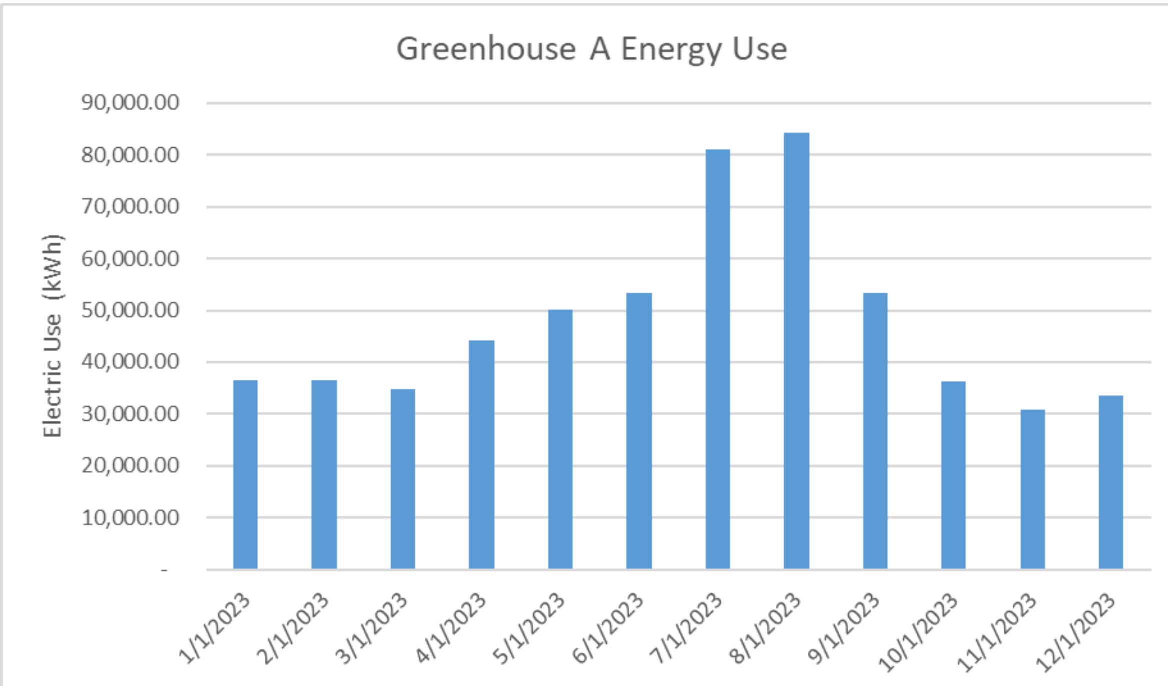

Figure 21: Greenhouse A monthly electricity use and demand.

Source: ERI. 2024d.

Greenhouse B

Greenhouse B is a 110-acre greenhouse of approximately 4.8 million square feet, located in Oxnard, California in CZ 5. The facility primarily grows cannabis, as well as cucumbers and tomatoes and displays some seasonal variations. The greenhouse also contains extensive curing, processing, and packaging spaces, which accounts for a significant portion of electricity usage. Figure 22 below summarizes electricity consumption at Greenhouse B, with average monthly electricity consumption at 990,525 kWh.

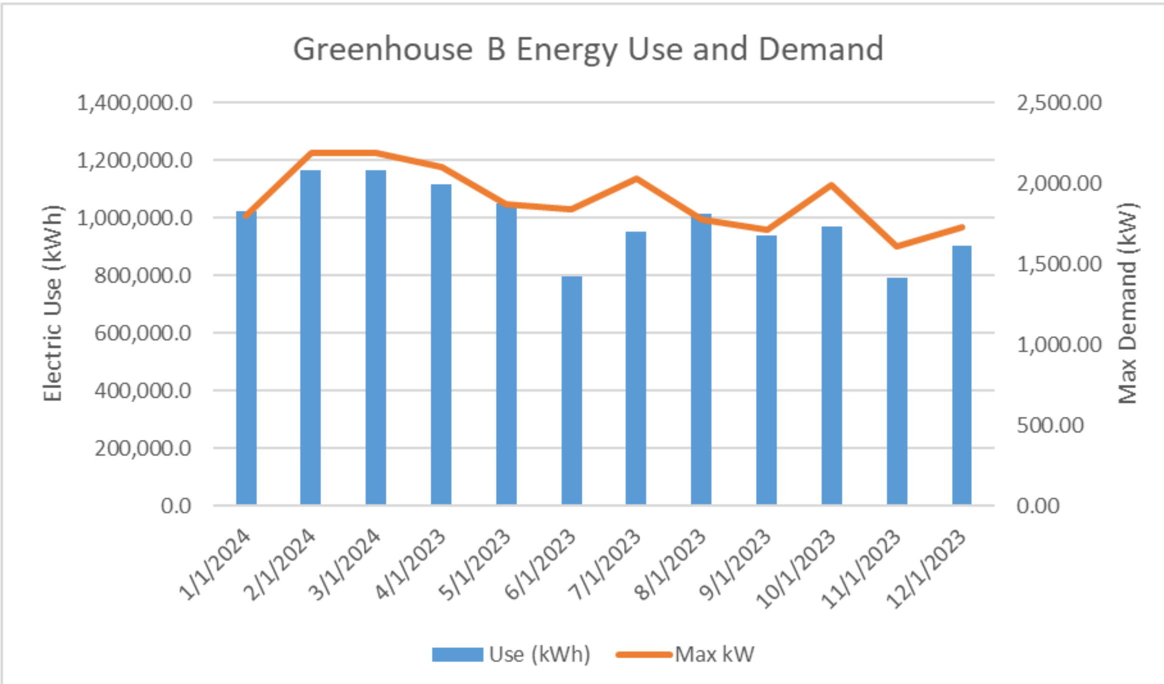

Figure 22: Greenhouse B monthly electricity use and demand.

Source: ERI. 2024d.

While Figure 22 represents electricity consumption at Greenhouse B, Figure 23 below demonstrates how the greenhouse generates electricity. Greenhouse B is equipped with three large, combined heat and power (CHP) generators, which it leverages generators as a primary source of heating hot water. Operations staff see the CHP system as being equally efficient at hot water generation compared to their boiler plant, with the added benefit of generating electricity that can be sold back to the grid. Because of this, Greenhouse B operates the CHP system based primarily on their heating needs rather than their electrical needs, and the facility is a significant net exporter to the grid throughout the year. Greenhouse B generated 48 GWh annually and used 12 GWh, exporting 36 GWh back to the grid from April 2023 through March 2024.

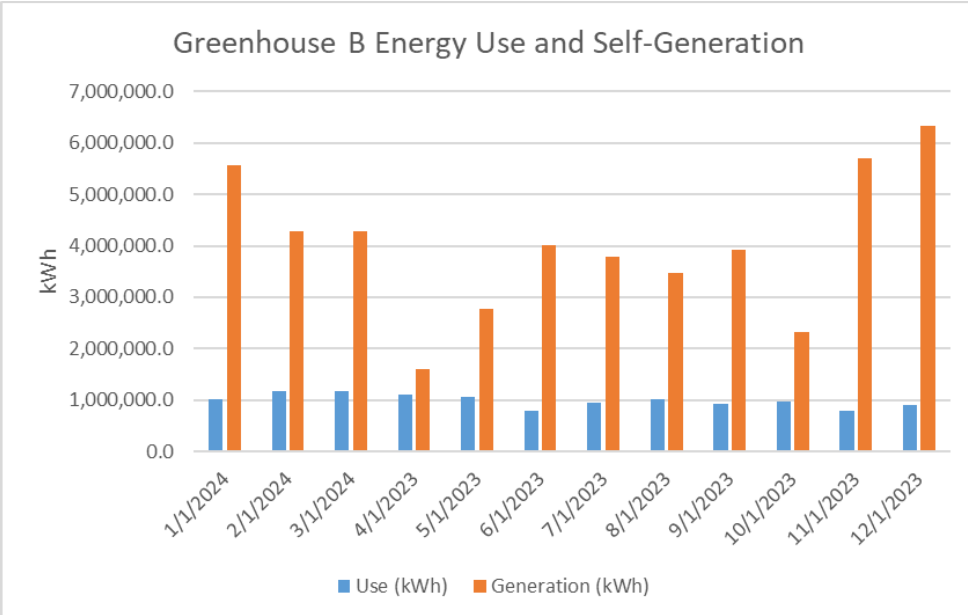

Figure 23: Greenhouse B monthly electricity use and self-generation.

Source: ERI. 2024d.

Loadshape Analysis

The team generated loadshapes for the California greenhouse market using anonymized electricity usage data from 66 customers with NAICS code 1114—which designates greenhouse, nursery, and floriculture production facilities—for months within 2021 to 2023. This data represents 1.4 percent of the 4,611 greenhouses and indoor farms growing food, floriculture, and cannabis in California.

The anonymized nature of the data limits the level of analysis. No data was provided for the size of facilities or systems in use, and only partial, limited visibility on crop type was available for some customers. Data included both greenhouse and fully indoor facilities.

Data from the 66 CEA facilities was grouped into three categories: large growers, with annual electricity use exceeding 1,000,000 kWh; medium growers, with annual electricity use between 100,000 kWh and 1,000,000 kWh; and small growers, with annual electricity use less than 100,000 kWh. The team excluded 17 facilities that had less than 12 months of data and 15 customers who consumed less than 10,000 kWh per year.

To compare loadshapes between sites that may have drastically differing monthly usage, the team normalized the data with the electricity usage intensity factor, which is calculated using monthly usage divided by the maximum monthly usage for all monthly data provided for each grower. A high-usage intensity indicates that a customer's usage for the month is close to their maximum monthly usage for the year; a low usage intensity indicates that a customer's usage for the month is low compared to their maximum monthly usage for the year.

The following loadshape analyses describe usage intensity rather than absolute electricity usage in kWh.

As illustrated by Figure 24, there was not a dominant, consistent loadshape observable across all 66 customers. Electricity usage intensity varied from less than 0.1 to greater than 0.9, with median quartiles between approximately 0.5 and 0.8, nearly every month of the year across all sites.

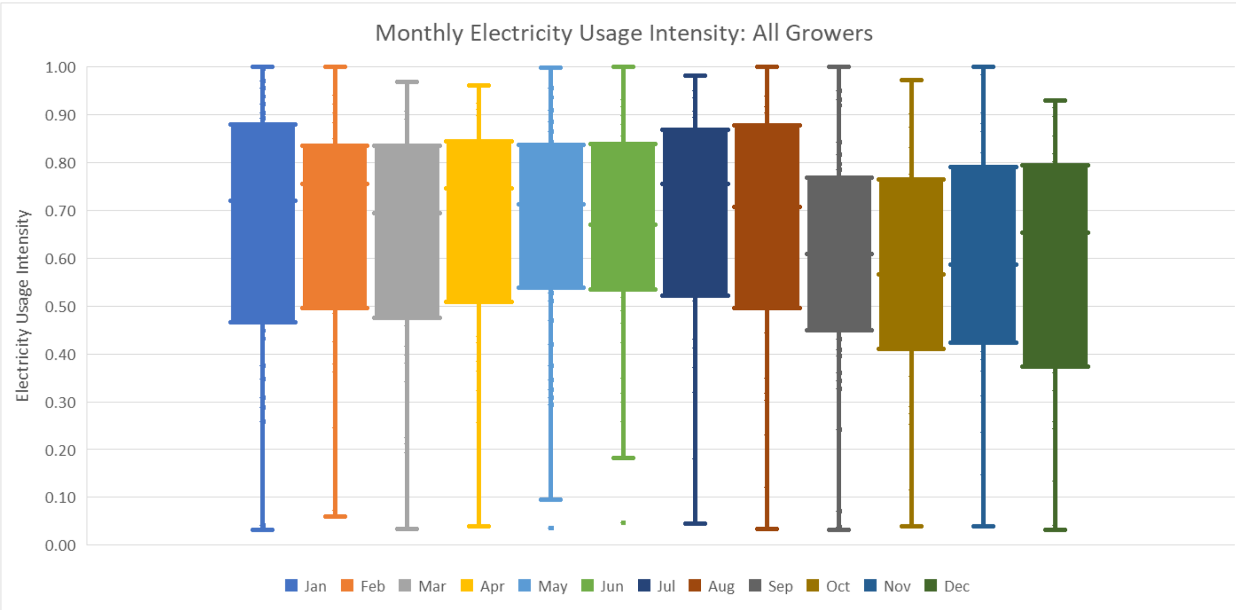

Figure 24: Anonymized electricity usage data loadshape—all growers.

Source: ERI. 2025.

However, sorting and separating data based on total annual usage revealed some patterns that may indicate differing dominant loads at facilities of different sizes, and opportunities for optimization through smart environmental controls.

Table 22: Anonymized dataset growers by size,

Electricity Use Category	Number of Customers
Insufficient Monthly Data	17
Low Electricity Usage Outlier	15
Small	10
Medium	16
Large	8
Total	66

Source: ERI. 2025.

Large Growers

Figure 25 shows the distribution of usage among large growers—defined as consuming greater than 1,000,000 kWh per year, with the highest energy consuming customer using 3,200,000 kWh per year. The lower median quartile shows that these growers generally have electricity usage intensity factors greater than 0.4 for every month of the year except for August. This indicates that each month, large growers typically have a base load that is at least 40 percent of their peak load. Median quartiles of the large grower dataset have usage factors between 0.4 and 0.9 for most months of the year. Maximum usage factors do not dip below 0.8, which indicates that the largest growers may have a base load that accounts for 80 percent of their peak load, leading to consistently high usage throughout the year.

Large growers in the dataset consume more electricity in winter. The winter data indicate that lighting drives electricity use, likely because large greenhouses typically use artificial lighting seasonally for photoperiod extension. For this reason, large growers may present a strong opportunity for energy savings from dimming, spectral tuning, and greenhouse daily light integral (DLI) lighting controls.

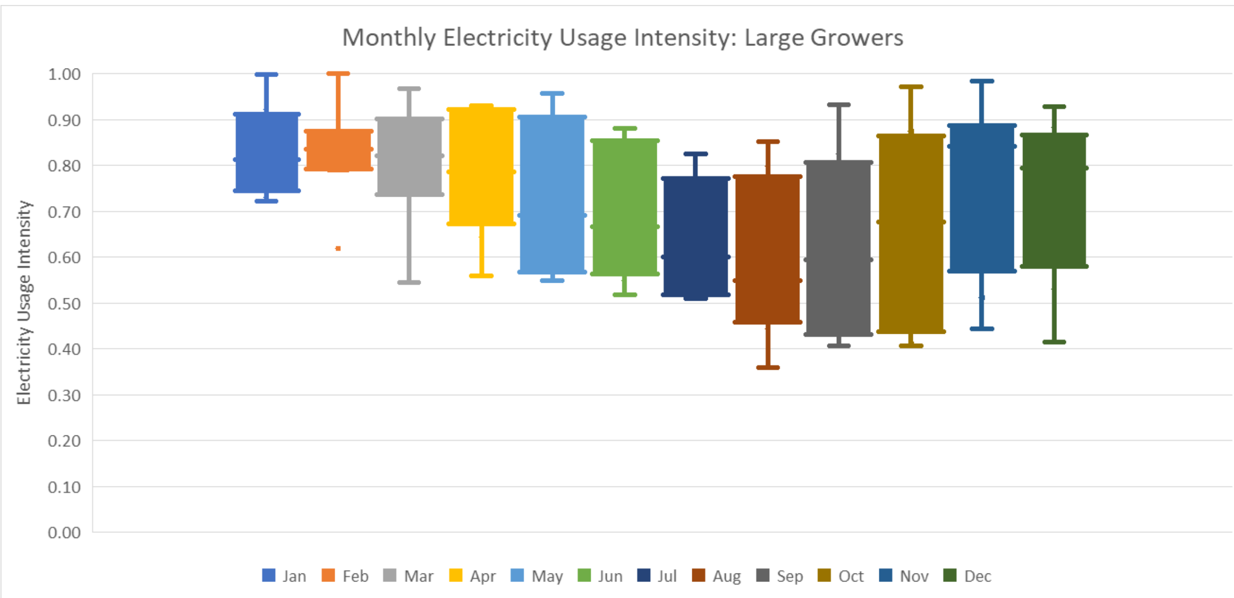

Figure 25: Anonymized usage data loadshape–large growers

Source: ERI. 2025.

Medium Growers

The distribution of usage intensity among medium growers—defined as consuming between 100,000 and 1,000,000 kWh per year—is wider than that of large growers, and is relatively flat throughout the year, with minor peaks during the winter and summer. Figure 26 shows that these growers have minimum electricity usage intensity factors of less than 0.1 for some months and as high as 0.4 in the shoulder season months of April and September. This indicates that each month, medium grower electricity usage can be highly variable, with a base load that is 10 to 40 percent of their peak load. Median quartiles of the medium grower dataset have usage factors between 0.4 and 0.9 for most months of the year. The maximum usage factor does not dip below 0.9, which indicates that some medium-sized growers may have usage over 90 percent of their peak at any time during the year.

The peaks indicate some of the greenhouse growers may not use as much supplemental lighting, and that HVAC and irrigation loads may be more balanced with lighting loads. For this reason, medium growers may present a strong opportunity for energy savings from HVAC measures like VPD optimization and automated greenhouse vent, fan, and curtain controls, as well as irrigation measures like variable-speed pumps and sensor-based irrigation controls.

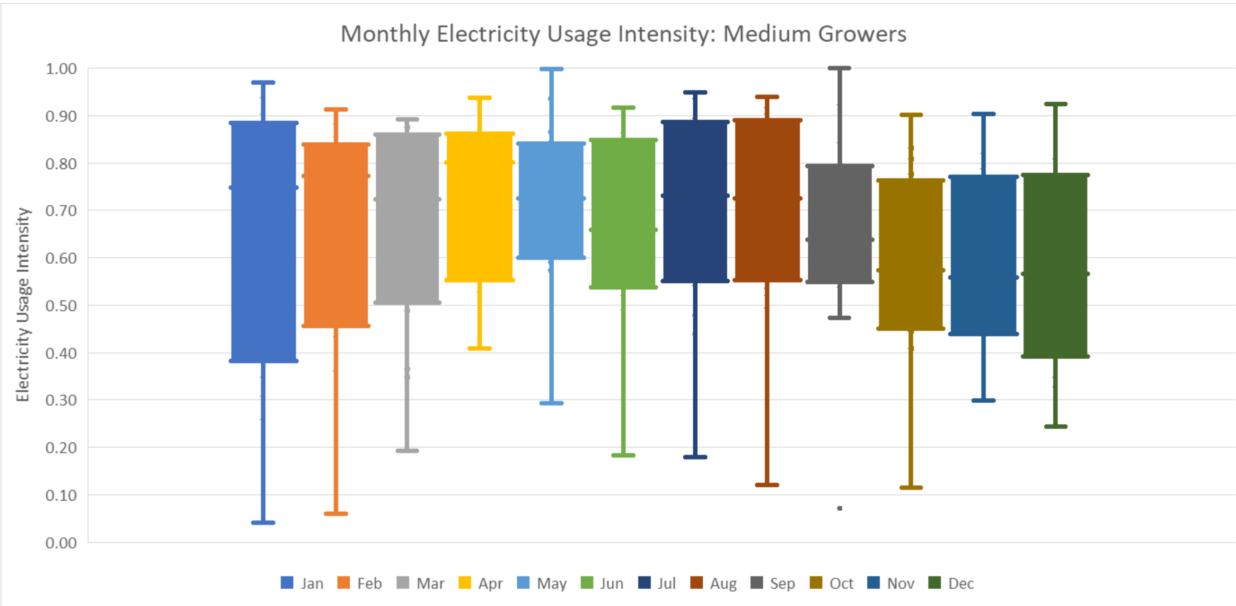

Figure 26: Anonymized usage data loadshape—medium growers.

Source: ERI. 2025.

Small Growers

The distribution of usage intensity among small growers—defined as consuming between 25,000 and 100,000 kWh per year—is similar to medium grower data and remains relatively flat throughout the year, with minor peaks in the winter and summer that correlate to peak lighting and cooling load, respectively. Figure 27 shows that these growers have minimum electricity usage intensity factors of 0.05 for some months and as high as 0.3 in January. This suggests that small growers are likely to have a high variance between their peak load and their base load, with base loads as low as 5 percent of their peak load. Median quartiles of the small grower dataset have usage factors between 0.25 and 0.9 for most months of the year, and the maximum usage factor ranges from 0.7 to 1.0, indicating that small growers' peak usage may occur at any point during the year.

The peaks shown in Figure 27 are more pronounced than with medium or large grower datasets, indicating that besides lighting and HVAC needs, small growers use less process equipment. For this reason, small growers may present diverse opportunities for energy savings from automating lighting and HVAC systems.

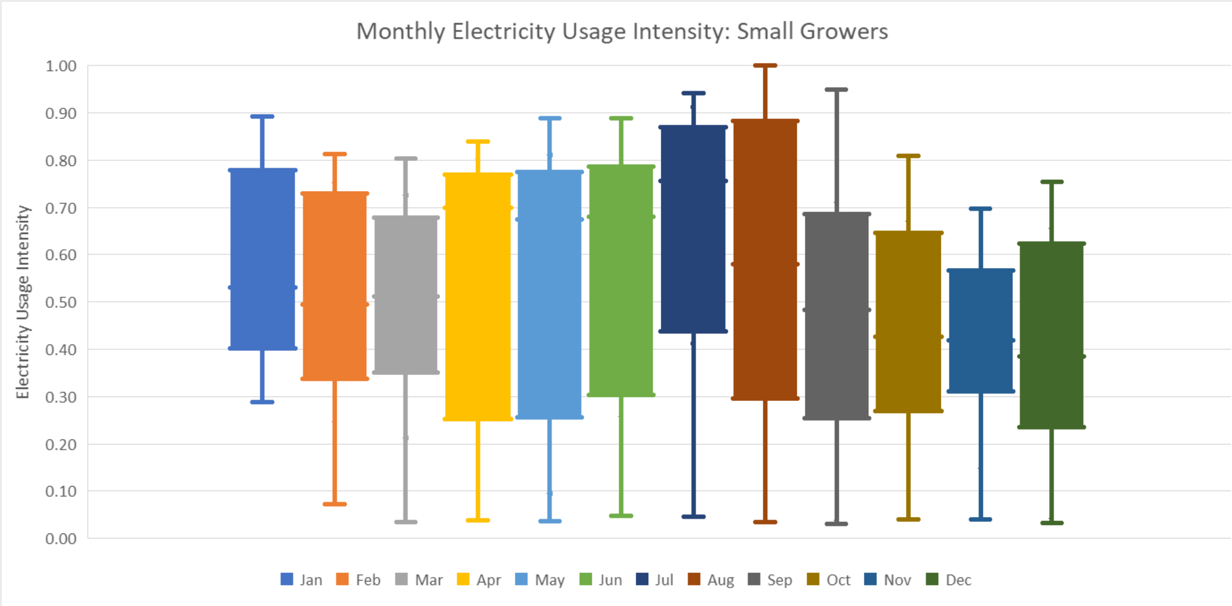

Figure 27: Anonymized usage data loadshape—small growers.

Source: ERI. 2025.

Field Demonstration Findings

The sections below provide detailed insights from the field demonstrations conducted in three California greenhouses and one indoor farm from October 2024 to April 2025.

The objectives of the field demonstrations were to:

1. Test smart automation and energy monitoring systems in representative environments in California CEA facilities.
2. Monitor energy at the circuit level to inform energy savings potential of smart controls measures.
3. Validate energy savings potential of automated, integrated, and intelligent CEA controls equipment.
4. Analyze barriers to adoption, energy savings, and non-energy benefits.

Field Demonstration Methodology

At each site, emerging technology controlled two zones per facility for a consistent comparison of baseline versus emerging technology. One zone implemented automated, integrated, and intelligent lighting, HVAC, and irrigation controls. One baseline zone used basic controls, such as time-switch lighting controls without integrated HVAC, irrigation controls, or artificial intelligence like cameras. Both zones had energy monitoring.

The team used energy monitoring data from controls systems to validate energy savings estimates. We observed several harvests to quantify the impact of CEA lighting, HVAC, and irrigation controls on energy and non-energy benefits; some plants, like orchids, are cultivated for longer than the field demonstration period.

All grower stakeholders and research partners had access to data from each field demonstration through an online dashboard maintained by the project's technology partner, Microclimates. The Microclimates software provided a graphic user interface that displayed real-time data using visualization tools. Field demonstration participants and the research team could view environmental and energy trend data for each environmental sensor and energy monitor for the six-month field demonstration period.

Field demonstration participants were encouraged to implement smart controls strategies throughout the field demonstration, if they were not doing so already. The project team suggested implementation strategies using insights gained from the granular environmental and energy data provided by the highly automated zone.

Field Demonstration Results

Figure 28 through Figure 31 in this section illustrate collected data for the four field demonstrations at two greenhouses growing lettuce, Greenhouses L1 and L2; one floriculture greenhouse growing orchids, Greenhouse F; and one indoor farm growing mushrooms, Indoor Farm M. Table 25 describes the four field demonstrations by CZ, crop type, size, and target process system for smart controls energy savings. Refer to Appendix D to review the scope, business benefits, lessons learned, and barriers to efficiency for each of the three field demonstrations in more detail.

Table 23: Field demonstration summary.

Field Demonstration ID	California Climate Zone (CZ)	Crop Type	Field Demonstration Size (ft^2)	Target Process System for Smart Controls Energy Savings
Greenhouse L1	CZ06	Lettuce	76,270	Horticultural lights, horizontal airflow fans
Greenhouse L2	CZ06	Lettuce	163,200	Horticultural lights, horizontal airflow fans
Greenhouse F	CZ03	Orchids	130,000	Heating pumps, vertical airflow fans
Indoor Farm M	CZ01	Mushrooms	1,000	All-electric HVAC, other process loads

Source: ERI. 2025a.

The following sections describe insights that can be used by California IOU EE programs to develop smart controls EE program offerings.

Automation Insights

Industry standard practice at the four field demonstration facilities demonstrated a high baseline level of sophistication for CEA environmental controls. Table 24 summarizes the level of control observed at the four field demonstration sites in 2024 and 2025.

Table 24: Field demonstration levels of control by system.

Environmental System	Greenhouses L1 & L2 Level of Control	Greenhouse F Level of Control	Indoor Farm M Level of Control
Heating	Level 1: Basic control (for setpoints) Level 3: Integrated control (for valves and pumps)	Level 1: Manual control (for setpoints) Level 3: Integrated control (for heating valves and pumps)	Level 1: Basic controls
Cooling & Dehumidification	Level 3: Integrated control	Level 2: Automated control (for fogger) Level 3: Integrated control (for other HVAC including curtains)	Level 0: Manual controls
Lighting	Level 3: Integrated control	Level 3: Integrated control	Level 0: Manual controls
Irrigation	Level 3: Integrated control	Level 3: Integrated control	N/A

Source: ERI. 2025a.

The field demonstration participant baseline represents businesses that had the time and resources to participate in a research study and may not accurately represent the industry standard practice of all California CEA growers. Three of the field demonstration participants are large greenhouses; as reported in the market assessment, these types of facilities are more likely to use automated, integrated, or intelligent controls like smart lighting, HVAC, and irrigation at Levels 2 through 4. The indoor farm is a small grower who did not have any automation system before participating in the field demonstration.

Energy Monitoring Insights

All field demonstration participants had never collected historical energy consumption data at the system level prior to participating in the study. The following insights relate to supplemental lighting, greenhouse ventilation fans, greenhouse heating pump, and indoor farm HVAC trends observed at demonstration sites.

SUPPLEMENTAL LIGHTING

Supplemental horticultural lighting systems are a large contributor to electricity use in greenhouses that grow vegetables like leafy greens. In the field demonstrations at Greenhouses L1 and L2, supplemental lighting system operation varied widely across lighting circuits, even those within the same zone. For example, some lights consumed no energy in the winter, but energy trends emerged in spring after around April 30. However, other lighting circuits were used throughout the winter months of December through February. Some lighting systems did not consume electricity for months at a time, like in March and April. Other lighting systems, such as the high-pressure sodium lighting system serving the vegetative greenhouse, did not turn on throughout the field demonstration period.

Figure 28 shows a springtime lighting sequence of operation at a lettuce greenhouse used for propagating young plants; the Y axis is in units of kilowatts (kW) and the X-axis is in days.

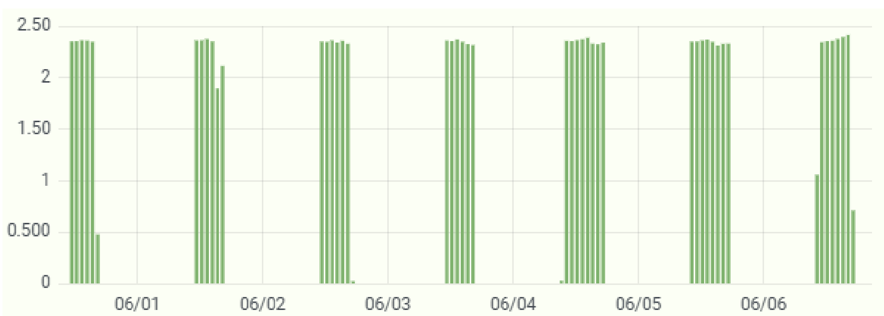

Figure 28: Daily leafy greens greenhouse supplemental lighting electricity consumption.

Source: ERI. 2025a.

This lighting circuit represents a portion of the 392 LED light fixtures serving Greenhouse L1, which has 24 lighting circuits. The automation system uses inputs from an outdoor weather station to turn on lights as required. The supplemental lighting equipment is turned on at 3:00 a.m. to extend the photoperiod, and stays on until 10:00 a.m., at which point natural sunlight can meet the grower's target for PPFD.

This is like a DLI control sequence of operation, but not quite. Photoperiod extension sequences of operation can result in overlighting crops and exceeding target DLI. Lighting power use does not vary significantly across the morning hours, which suggests that the fixtures are turned on in response to weather station data and are not being dimmed based on data from light sensors in the greenhouse at the plant canopy level.

GREENHOUSE VENTILATION FANS

Figure 29 shows a springtime ventilation fan sequence of operation at a lettuce greenhouse used for finishing crops; the Y axis is in units of kW and the X-axis is in days.

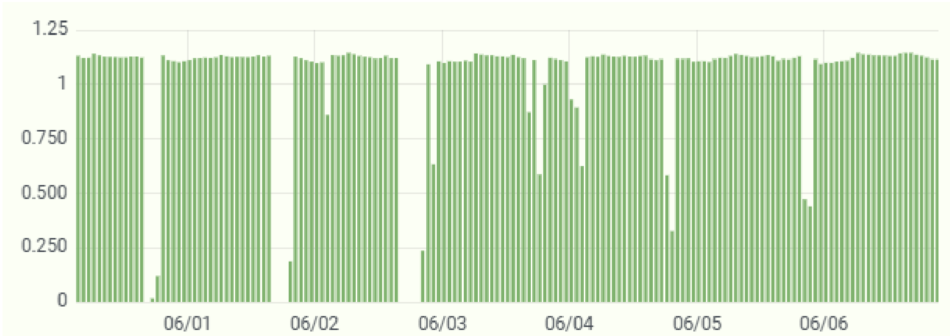

Figure 29: Daily leafy greens greenhouse ventilation fan electricity consumption.

Source: ERI. 2025a.

This fan circuit represents a portion of the 11 fans serving Greenhouse L2, which has two fan circuits. The horizontal airflow fan system operation at Greenhouse L2 was mostly consistent, with some variation. The automation system uses inputs from climate sensors in the greenhouse to turn on fans as required, and fans run nearly 24/7 to maintain minimum airflow in the greenhouse for plant growth and development. They are also used to maintain greenhouse space temperature.

When fans are running, there are not many instances of partial demand, which suggests that while fans are turned on in response to climate sensor data, variable-speed fans are not being used. Survey results showed that 45 percent of respondents use single-speed ventilation fans.

GREENHOUSE HEATING PUMPS

Figure 30 shows a springtime heating pump sequence of operation for an orchid greenhouse; the Y axis is in units of kW and the X-axis is in days.

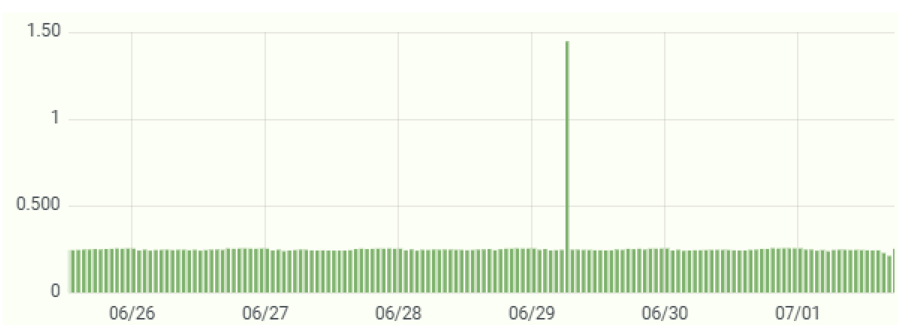

Figure 30: Daily orchid greenhouse heating pump electricity consumption.

Source: ERI. 2025a.

This heating pump circuit represents a circulation pump for a hot water heating system serving Greenhouse L2, which operates two bottom heating circulation pumps and one top heating pump in its hot zone. Heating pump operation at Greenhouse F was observed to be consistent, although there were some unexplained spikes in demand. The automation system uses inputs from sensors in the greenhouse to turn on top and bottom heating pumps as required to maintain a target space temperature setpoint, but these single-speed heating pumps run nearly constantly.

INDOOR FARM HVAC

Figure 31 shows exhaust fan trends for a very small indoor mushroom farm over the six-month field demonstration period.

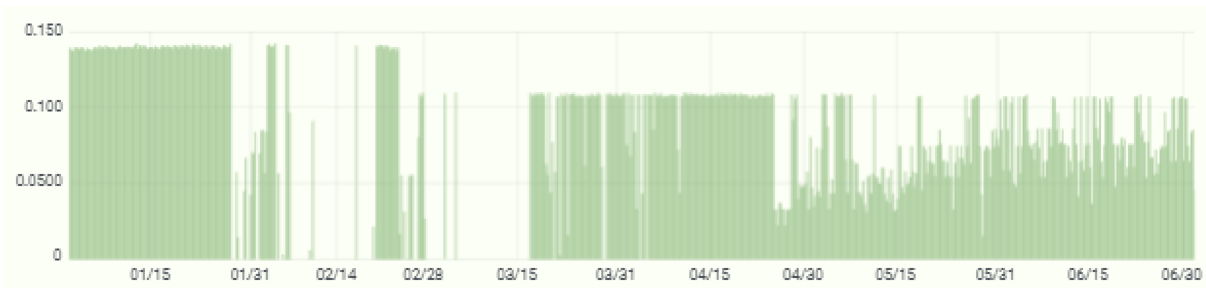

Figure 31: Mushroom farm exhaust fan electricity consumption trends.

Source: ERI. 2025a.

This grow room circuit represents the long-term energy consumption trends for an exhaust fan serving Indoor Farm M. Grow room exhaust fan operation at Indoor Farm M was quite variable, both seasonally and throughout a given day. The automation system uses inputs from sensors in the indoor farm to ramp the exhaust fan up and down as required to maintain a target indoor farm space temperature setpoint.

At the beginning of the field demonstration period, the exhaust fans ran 24/7, but the operation takes a two-month break in springtime. At the end of the field demonstration period, trends show exhaust fans implementing a sequence of operation that suggests variable-speed fan operation in response to sensors in the grow room.

Market Assessment Recommendations

This section shares the cost-effective EE and demand response measures for smart CEA environmental controls identified in the market assessment and explores the impact of the market assessment. Additionally, the team used inputs from the literature review, surveys, interviews, and site visits to create measure descriptions for controls strategies that reduce energy use from greenhouses and indoor farms.

Measure Descriptions

This market assessment determined that each CEA process system has multiple controls measures with promising energy savings potential. Table 25 demonstrates that California IOUs can uncover substantial savings claims within three CEA process systems.

Table 25: Smart CEA environmental controls measure descriptions.

Measure System	Measure Name	Measure Description	Process Electricity Savings Potential
Lighting	Dimming Controls	Reduction in horticultural light fixture wattage coincides with improvements in PPE.	8% increase in PPE when fixtures are dimmed 50%
Lighting	Spectral Tuning	Tune horticultural lighting spectrum for EE fixture PPE by applying light recipes with more red diodes.	40% or more
Lighting	Daily Light Integral (DLI) Controls	Reduce horticultural lighting system operation to maintain consistent DLI based on predictive or measured solar data.	20–69% in greenhouses
HVAC	Automated Greenhouse Vent Control	Automate greenhouse ventilation controls to reduce unnecessary fan operation.	17–21%
HVAC	Automated Greenhouse Curtain Control	Reduce solar radiation entering greenhouses to reduce cooling demand by employing shade curtains.	50–60%
HVAC	Automated CEA Fan Control	Automate CEA HVAC fan controls to reduce unnecessary operation.	Up to 36%
HVAC	VPD Optimization	Optimize Vapor Pressure Deficit (VPD) for specific crops, and optimize space temperature and humidity setpoints for optimum EE while maintaining target VPD.	25–50%
Irrigation	Variable-Speed Pump Control	Equip irrigation pumps with variable speed motors and control pump speed in reference to loop pressure, allowing reduced pump speeds when partial irrigation capacity is required.	27–35%
Irrigation	Sensor-Based Irrigation Controls	Control irrigation valves based on substrate moisture content rather than on timed schedules.	33–50%

Impact of Market Assessment Findings

The results of the market assessment indicated that incentive programs for controls measures—when implemented concurrently with energy monitoring and standardized data transfer protocols—will accelerate the adoption of smart environmental controls in California CEA facilities.

The impact of the market assessment's findings on the CEA market and key industry stakeholders including California IOUs include:

- California's CEA market of over 4,600 greenhouses and indoor farms continues to expand, and more market transformation is necessary to reduce energy consumption via emerging technologies like smart environmental controls.
- This market assessment identified incentive programs for the smart CEA environmental controls measures that will not be affected by the 2025 version of California's energy code.
- Standardized energy monitoring data is crucial for measurement and verification of the energy savings of CEA controls measures.
- Lighting controls measures, such as DLI controls, have the greatest electric savings potential for greenhouses, especially those located in southern California.
- Spectral tuning is a lighting controls measure that can save energy at most greenhouses and indoor farms, but it may not have a strong value proposition for all CEA growers.
- Increases in industry standard practice for PPE for horticultural lighting heavily influence the electricity savings of CEA lighting controls measures.
- HVAC controls measures present a substantial savings opportunity, but measurement and verification may be more complex due to the number of systems involved at each operation.
- Irrigation controls measures offer the smallest electric savings potential but will be present at every CEA facility in California regardless of type, size, or location.

Technology Roadmap

These lessons learned from the market assessment and field demonstrations combine to create a technology roadmap, which offers a strategic direction for program development, identifying cost-effective measures, and presenting program offerings—including the need for new or updated measure packages. The findings also support utilities in designing EE measures for controls products, with a focus on innovative strategies for deemed or hybrid approaches.

This technology roadmap for smart CEA controls identified and evaluated environmental controls technologies with the highest potential for energy savings and demand response, proposing paths to address market barriers and provide intervention strategies for market implementation.

The savings estimates described in this section were generated using a custom energy savings calculator that leverages historical weather data for the 16 California CZs. The team used data from the four field demonstrations to confirm the energy savings model's baseline controls strategies and calibrate the energy savings estimated from smart CEA environmental controls strategies (ERI 2025b).

We recommend two measures for smart CEA environmental controls in this technology roadmap for IOU EE program development. Both measures are for greenhouses, as the savings potential is greater for this market than for indoor farms due to the large number of greenhouses in California; more details on this market size are available in the Market Overview section.

Program Pathways

Data from commercial CEA businesses operating in California supports smart CEA controls program design with actual energy consumption and demand data from multiple sites across the state. The impact of the field demonstrations' findings on the CEA market and key industry stakeholders including California IOUs include:

1. **Confirm the Level 0 to Level 4 baseline level of control for CEA lighting, HVAC, and irrigation controls, based on the results of this study's surveys, interviews, site visits, and field demonstrations.** Document the IOU-specific baseline equipment by crop type, facility size, or other parameters using the operational details described in site visit and field demonstration reports to develop a standalone work paper.
2. **Develop a deemed measure package for greenhouse supplemental lighting DLI controls.** The proposed changes to the California Energy Code Title 24, Part 6 requirements for greenhouses may include a requirement for DLI controls; this gives IOUs three years to implement an EE program for DLI controls before the energy code requires this automation strategy. The recommended calculation methodology can be modified and used as the permutations for a new deemed measure based on CZ, crop type, or DLI target. The team recommends sharing the measure idea with the California Technical Forum team to determine the next steps to launch a deemed rebate program for DLI controls.

A specialized daylighting measure for horticultural process lighting is one greenhouse DLI controls measure for supplemental lighting systems that does not currently exist in the California eTRM. This measure reduces energy consumption by using automated, integrated, and/or Level 2 through Level

4 intelligent controls that modulate lighting power to meet a set DLI target. Error! Reference source not found. summarizes the average savings for DLI controls across the four major types of CEA crops that typically use supplemental lighting in California's CZ. The table uses an example 10,000-square-foot greenhouse with a glazing visible light transmittance (VLT) of 0.7, which operates LED supplemental light fixtures with a PPE of 2.8 μmol/J. The estimated supplemental light fixture quantity is a function of square footage, but does not account for variations in light fixture quantity by CZ. Refer to Appendix E for detailed savings metrics for each of the 16 California CZ.

Table 26: California greenhouse DLI controls measure savings potential.

Crop Type	Light Fixture Quantity	Average Electricity Savings (kWh)	Average % Savings	Average Demand Reduction (kW)	Average Area-Normalized Electricity Savings (kWh/ft^2)
Leafy Greens	172	431,582	64%	49	43
Tomato	179	364,339	78%	52	36
Cannabis – Veg	417	951,246	58%	109	95
Cannabis – Flower	500	692,368	53%	79	69

Source: ERI. 2025b.

The average savings observed across the four crop categories reflects the higher end of the market assessment's savings estimate of 20 to 69 percent, as shown in Table 25. This is likely due to the influence of multiple California CZ in the southern part of the state receiving significant solar radiation year-round. This measure would be applicable across the 1,555 greenhouses growing food and cannabis crop, which make up nearly 92 million square feet of facilities across California.

3. **Develop a deemed measure package for installing a variable frequency drive on agricultural circulation fans in greenhouses.** The recommended calculation methodology can be modified and used as the permutations for a new deemed measure based on CZ, crop type, or DLI target. We recommend sharing the measure idea with the California Technical Forum team to determine next steps for launching a deemed rebate program that could provide variable frequency drive (VFDs) for greenhouse ventilation fans.

Currently, there is no specialized agricultural fan measure for VFD controls for greenhouse ventilation fans in the California eTRM. Table 27 summarizes the average savings for ventilation fan VFD controls in California's CZ. As before, the table uses a 10,000-square-foot greenhouse served by 20 1.5-horsepower ventilation fans, which are controlled to a 68°F heating setpoint. Refer to Appendix F for detailed savings metrics for each of the 16 California CZ.

Table 27: California greenhouse ventilation fan VFD measure savings potential.

Crop Type	Average Electricity Savings (kWh)	Average % Savings	Average Demand Reduction (kW)	Average Area-Normalized Electricity Savings (kWh/ft^2)
All CEA Crops	123,342	63%	14	12

Source: ERI. 2025b.

This measure would be applicable across the 3,600 greenhouses growing floriculture, food, and cannabis crops, which make up nearly 300 million square feet of facilities across California.

4. **Develop a unique outreach strategy for hard-to-reach (HTR) CEA businesses in IOU territory.** Many businesses active in the CEA market are more likely to be HTR customers because concentrations of cultivation facilities are in counties that satisfy the HTR geographic criteria.[2] CEA businesses in these counties are considered HTR customers if they meet one other HTR criteria, and the study found that CEA businesses may meet several other HTR criteria more often. For example, these businesses may operate in leased buildings, their owners or operators may not speak English as a first language, and enterprises may be micro-businesses with less than 25 employees.
5. **Leverage controls equipment manufacturers and distributors to encourage technology transfer and recruit CEA customers and contractors to participate in new CEA controls incentive programs and/or project marketplaces.** Controls equipment manufacturers can help confirm the incremental cost of different levels of control for CEA lighting, HVAC, and irrigation controls for IOU territories. Consider implementing rebate programs upstream to accelerate adoption of smart CEA environmental controls.

[2] Geographic HTR criteria: Businesses in areas other than the United States Office of Management and Budget combined statistical areas of the San Francisco Bay Area, the Greater Los Angeles Area and the Greater Sacramento Area or the Office of Management and Budget metropolitan statistical areas of San Diego County.

Appendices

Appendix A: California Cannabis Licensees by County

California County	Indoor Licensee Count	Mixed Light Tier 2 Licensee Count
Alameda	72	2
Calaveras	3	6
Colusa	3	0
Contra Costa	19	1
Del Norte	2	0
Fresno	3	3
Humboldt	21	69
Imperial	3	0
Inyo	0	1
Kern	7	9
Lake	0	6
Los Angeles	313	1
Marin	1	0
Mendocino	7	25
Merced	4	0
Mono	1	0
Monterey	20	136
Nevada	5	8
Orange	13	0
Riverside	86	14

California County	Indoor Licensee Count	Mixed Light Tier 2 Licensee Count
Sacramento	97	15
San Benito	4	0
San Bernardino	94	8
San Diego	7	1
San Luis Obispo	0	4
San Francisco	11	0
San Joaquin	4	0
San Mateo	0	3
Santa Barbara	0	18
Santa Clara	9	0
Santa Cruz	9	15
Shasta	12	0
Solano	2	0
Sonoma	20	2
Stanislaus	15	1
Trinity	5	26
Ventura	0	1
Tulare	4	0
Yolo	1	8
TOTAL	879	383

Source: DCC. 2024. Unified Cannabis License Search.

Appendix B: Survey Questionnaire

Please answer the following questions to best of your knowledge:

**Mandatory question*

Facility Details

Please tell us about what crops you grow and how you cultivate them.

1. *Which of these options best describes how you grow at your California operations?
    a. Greenhouse
    b. Indoor
    c. Indoor Vertical
2. *Which of these options best describes the primary crop you grow at your California operations?
3. Ornamentals / floriculture / nursery
4. Food (vegetables, tomatoes, herbs, berries, mushrooms, etc.)
5. Cannabis
6. *Where is your facility located in California? Enter the nearest city.
    a. __________
7. When was your facility built? If recently retrofitted, use the year of the most recent major renovation or addition.
    a. __________
8. What is the total square footage of the facility that is dedicated to growing plants?
    a. __________

Control System Details

Please tell us about the horticultural controls systems in use at your facility. (A controls system refers to the hardware and software that monitors environmental conditions and manages lighting, HVAC, and/or irrigation systems to maintain target temperature, humidity, light intensity, and nutrient levels for crop growth and development.

9. Which of these options best describes your facility's controls systems?
    a. Lighting, HVAC, or irrigation systems are not controlled by hardware or software***allow responder to skip following questions***
    b. Lighting, HVAC, or irrigation systems are controlled by programmable hardware (example: thermostats)
    c. Lighting, HVAC, or irrigation systems are controlled by software on a computer or phone application.
10. *What is your level of overall satisfaction with your facility's controls systems (including lighting, HVAC, irrigation)?
    a. Very Satisfied
    b. Satisfied
    c. Neutral
    d. Dissatisfied
    e. Very Dissatisfied

11. Which of these options best describes the level of automation within your current **Lighting** controls system?
    a. No control system (on/off switch)
    b. Basic (manual setpoints and schedules)
    c. Automated (remote monitoring and control)
    d. Integrated (simultaneous monitoring and control of multiple systems)
    e. Intelligent (machine learning, AI or data-driven logic monitoring and control)
12. *Which of these options best describes your approach to monitoring energy consumption of your **Lighting** system?
    a. Do not monitor energy consumption.
    b. Monitor energy consumption at the facility level.
    c. Monitor energy consumption at the system level.
13. Please share the make and model specifications of your current controls system.
    a. Lighting [____]
14. Which of these options best describes the level of automation within your current **HVAC** controls system?
    a. No control system (on/off switch)
    b. Basic (manual setpoints and schedules)
    c. Automated (remote monitoring and control)
    d. Integrated (simultaneous monitoring and control of multiple systems)
    e. Intelligent (machine learning, AI or data-driven logic monitoring and control)
15. *Which of these options best describes your approach to monitoring energy consumption of your **HVAC** system?
    a. Do not monitor energy consumption.
    b. Monitor energy consumption at the facility level.
    c. Monitor energy consumption at the system level.
16. *Which climate systems are managed by your **HVAC** controls system? Select all that apply.
    a. Heating
    b. Ventilation and Circulation (including fans and greenhouse vents)
    c. Cooling
    d. Dehumidification
    e. Greenhouse Curtain (climate screen; thermal or shade)
17. Please share the make and model specifications of your current **HVAC** controls system.
    a. HVAC [____]
18. Which of these options best describes the level of automation within your current **Irrigation** controls system?
    a. No control system (on/off switch)
    b. Basic (manual setpoints and schedules)
    c. Automated (remote monitoring and control)
    d. Integrated (simultaneous monitoring and control of multiple systems)

e. Intelligent (machine learning, AI or data-driven logic monitoring and control)

19. *Which of these options best describes your approach to monitoring energy consumption of your **Irrigation** system?
    a. Do not monitor energy consumption.
    b. Monitor energy consumption at the facility level.
    c. Monitor energy consumption at the system level.
20. Please share the make and model specifications of your current **Irrigation** controls system.
    a. Irrigation [____]

Facility System Details

Please tell us about your facility's lighting, HVAC, and irrigation equipment.

21. *Which of these options best describes your facility's **cooling** equipment? Select all that apply.
    a. Natural Ventilation / Fans
    b. Evaporative Cooling (pad & fan or misting/fogging systems)
    c. Packaged Air Conditioner or Heat Pump System
    d. Gas Chiller
    e. Electric Chiller
    f. Other (please specify)
    g. None of the above
22. *Which of these options best describes your facility's **heating** equipment? Select all that apply.
    a. Gas Unit Heaters
    b. Gas Infrared Heaters
    c. Gas Boiler / Hydronic Heating System
    d. Electric Heat including Heat Pumps
    e. Propane/Fuel Oil Heating system
    f. Wood Heat
    g. Other (please specify)
    h. None of the above
23. *Which of these options best describes your facility's **ventilation** equipment? Select all that apply.
    a. Natural ventilation (Gable, Venlo, etc.)
    b. Single speed fans
    c. Fans with VSD
    d. Other (please describe)
24. *Does your facility use greenhouse curtains?
    a. Yes
    b. No
    c. N/A

25. Please describe the type of curtains used within your greenhouse (Example: One thermal screen and one shade curtain).
    a. ____
26. *Which of these options best describes your facility's lighting equipment? Select all that apply.
    a. No horticultural lighting
    b. Fluorescent (T-type tube lights)
    c. High Pressure Sodium and/or Metal Halide
    d. LED
27. *To the best of your ability, please describe the quantity and capacity of your facility's irrigation pumps (Example: Two 15-horsepower pumps).
    a. ____

Energy Efficiency (EE) Details

If you like, please tell us a bit more about your energy goals so that we can ensure efficiency programs are effective at reducing barriers to EE for growers.

28. What was your facility's natural gas usage for the past 12 months?
    a. __________ therms
29. What was your facility's natural gas usage for the past 12 months?
    a. __________ kWh
30. What are your primary concerns with implementing EE upgrades?
    a. First Cost of Materials and Labor for Installation
    b. System Performance
    c. Training Needed for New Systems
    d. Labor (availability of resources)
    e. Other ______________
31. If an EE project is proposed which involves retrofitting existing equipment to reduce energy consumption & costs, what is an ideal payback period that you are willing to consider for the project?
    a. <1 year
    b. 1 – 2 years
    c. 2 – 5 years
    d. 5 – 10 years
32. Are you considering any facility upgrades or EE improvements?
    a. __________
33. Based on your best estimation, what do you proportion of growers like you are using automated controls at their farm?
    a. __________ (value from 0-100)

Appendix C: Site Visit Reports

Indoor Farm #1

Figure 32: Cannabis flowering room at Indoor Farm #1.

Source: ERI. 2024e.

Indoor Farm #1 operates a 100,000-square-foot cannabis facility in Sacramento, California, as shown in Figure 32 above. The facility is serviced by two 2,000 amp meters, or 480V service. The facility was renovated in 2021 to split the facility into four 7,200-square-foot flowering rooms, and one 3,600-square-foot vegetative room.

The facility has varying levels of system automation, which Table 28 describes by environmental system type.

Table 28: Levels of control by system at Indoor Farm #1.

Environmental System	Level of Control
HVAC	Level 1 – basic thermostat control
Lighting	Level 0 – manual on/off switch control
Irrigation	Level 2 – automated control

Source: ERI. 2024e.

HVAC EQUIPMENT AND CONTROLS

The grow rooms are serviced by multiple HVAC units rated to provide 400 tons of cooling capacity. The facility primarily operates Desert Aire units, as shown in Figure 33 below, but uses one Cultiva unit to serve a flowering room and one Aaon unit to service office spaces. All HVAC units operate based upon target temperature and relative humidity setpoints, but the Desert Aire units do not have VSD, while the Cultiva and Aaon units do. For monitoring grow room conditions, each grow room uses two environmental sensors—measuring temperature, CO_2 levels, and relative humidity—and one Level 1 HVAC control central thermostat.

The farm uses factory controls for most HVAC units. However, they use custom controls Desert Aire HVAC units, as these share a flowering room with the Cultiva unit, which are shown in Figure 34 below.

Figure 33: HVAC system serving Indoor Farm #1.

Source: ERI. 2024e.

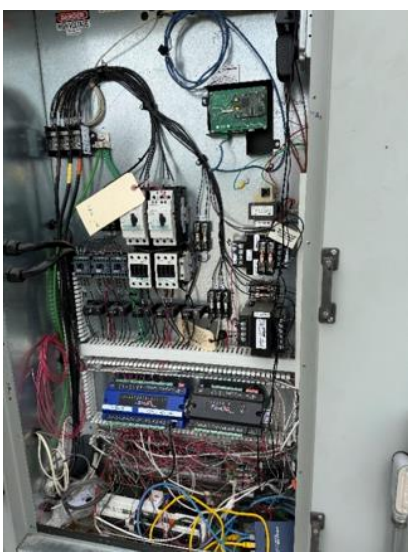

Figure 34: Custom HVAC controls hardware serving Indoor Farm #1.

Source: ERI. 2024e.

Each grow room is serviced by approximately two dozen circulation fans, which do not have VSDs and are operated using on/off control switches.

Three of the flowering rooms have supply air and return air ductwork located above the growing canopy, while the final flowering room has supply air ducts above the growing canopy and return air ducts below the growing canopy.

At the site visit, Indoor Farm #1 operators reported historical issues with HVAC control. Their principal concerns were valve malfunctions within the HVAC units, which do not have fault detection and diagnostics system or alarm systems. Operators are interested in improving the remote automated control capabilities of the HVAC system, as nighttime control is difficult with the current on/off controls. The current operational procedure is to leave the HVAC system running overnight with no on-site or remote monitoring. In the case of any HVAC system malfunction, employees must be on-site to operate the HVAC system.

LIGHTING EQUIPMENT AND CONTROLS

Most of the grow rooms are lit with GavitaPro 1000 W double-ended high-pressure sodium fixtures. One flowering room has additional under-canopy Thrive Agritech 120 W LED lighting, as shown in Figure 35. Operators plan to install the Thrive Agritech fixtures in the other flowering rooms in 2024. The vegetative room and one of the other flowering rooms use a 'checkerboard' lighting layout with the GavitaPro fixtures and Fluence 630 W LEDs, as shown previously in Figure 32.

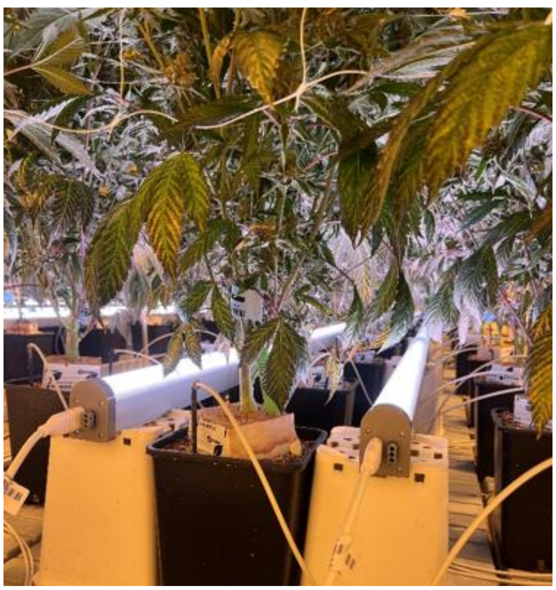

Figure 35: Under-canopy LED lighting at Indoor Farm #1.

Source: ERI. 2024e.

All horticultural lighting at Indoor Farm #1 is operated using Level 0 lighting on/off controls. The daily flowering room lighting schedule of 12 hours on, 12 hours off, and the daily vegetative room lighting schedule is 18 hours on, 6 hours off. The overall lighting schedule is correlated to the occupancy schedule, such that lights are on during the day starting around 6:00 a.m. Lighting equipment does not receive information from environmental sensors in the grow rooms.

IRRIGATION EQUIPMENT AND CONTROLS

Indoor Farm #1 uses a standalone OpenSprinkler Level 2 automated drip irrigation system to water plants. Each flower room consumes an average of 1,450 gallons of water per day, and every plant receives water and nutrients from two drippers, as shown in Figure 36 below.

Figure 36: Drip irrigation system at Indoor Farm #1

Source: ERI. 2024e.

The watering schedule is automated and controlled by OpenSprinkler's online software platform, as shown in Figure 37. There are two irrigation sensors per row which monitor substrate temperature, moisture content, pH, and electric conductivity (EC). These readings are reported on an Aroya monitoring dashboard but do not contribute to the control logic.

The automated watering schedule begins to irrigate plants when the lights turn on in intervals of 8 minutes on, 22 minutes off for the first three hours. After this initial period, the plants are watered for 8 minutes each hour on the hour until the lights are turned off.

Figure 37: Aroya dashboard at Indoor Farm #1.

Source: ERI. 2024e.

Greenhouse #1

Figure 38: Cannabis flowering room at Greenhouse #1.

Source: ERI. 2024e.

Greenhouse #1 is a 20,000-square-foot greenhouse located in California City, California. The business grows cannabis in a completely off-grid facility, initially by necessity due to a lack of utility capacity in the area. The operators have used this as an opportunity to develop a testbed for growing high-quality cannabis with a low carbon and water footprint. The facility consists of three greenhouse ranges connected by a common head house, with a small, attached warehouse containing mechanical, administrative, and processing spaces.

All greenhouse systems are highly automated and tightly integrated through a unified controls system. This high degree of integration is leveraged to minimize the water and energy inputs to the facility, allowing the facility to be powered largely by a solar and battery storage system with a small diesel generator that runs primarily in the winter. The greenhouse controls system leverages predictive weather and cloud cover forecasting to precisely balance self-generation and battery capacity with HVAC, lighting, and irrigation needs and loads. Table 29 describes the level of control by environmental system type.

Table 29: Levels of control by system at Greenhouse #1.

Environmental System	Level of Control
HVAC	Level 4 – integrated and intelligent control
Lighting	Level 4 – integrated and intelligent control
Irrigation	**Level 4 – integrated and intelligent control**

Source: ERI. 2024e.

HVAC EQUIPMENT AND CONTROLS

The greenhouses are cooled with motorized roof peak vents, exhaust fans, and an evaporative "wet wall"—also referred to as a pad and fan system, as shown in 39 below. Motorized louvers on both the fan and wet wall sides of the greenhouse keep the greenhouse sealed when exhaust fans are not operating to ensure consistent conditions across the greenhouse and select areas within each greenhouse are equipped with circulation fans attached to flexible ducting. At the time of the site visit, these were being tested to improve climate consistency throughout the greenhouse; the facility operators indicated they are satisfied with their performance and intend to expand their use to the rest of the facility.

Greenhouses are heated by propane unit heaters located above-bench and hydronic radiant slab heating in the floors. Additionally, the common head house is equipped with unit heaters, which are used during colder weather conditions to pre-heat and dehumidify air before it is drawn into the greenhouse zones, as shown in Figure 40. Hot water for the radiant slab floors is generated by a 199,000 Btu per hour (MBH) tankless condensing water heater.

Figure 39: Greenhouse #1 wet wall.

Source: ERI. 2024e.

Figure 40: Greenhouse #1 head house heaters.

Source: ERI. 2024e.

All HVAC systems are controlled by an integrated Ridder Synopta Level 4 controls system, based upon target temperature and relative humidity setpoints. The Ridder system allows for a high degree of communication between various systems, sensors, and external data sources. The facility uses sensors which monitor temperature, relative humidity and vapor pressure deficit to inform HVAC controls. All energy-consuming equipment—such as pumps, fans, and motors—are equipped with direct feedback to the control schemes that take advantage of an advanced onsite weather station, as well as external weather data sources for predictive forecasting for lighting shades and solar array output.

LIGHTING EQUIPMENT AND CONTROLS

Lighting systems are a mix of iGrow induction—also known as electrodeless fluorescent—horticultural lighting and contractor-style string lighting. Some zones don't receive sufficient sunlight due to their proximity to opaque exterior walls and are equipped with 1,000-watt, double-ended high-pressure sodium horticultural fixtures, as shown in Figure 41 below. All zones are also equipped with both partial shading and blackout curtains, also called climate screens. The curtains are controlled through the integrated system and informed via predictive forecasting.

Figure 41: Greenhouse #1 typical flowering lighting zone.

Source: ERI. 2024e.

Lighting and screens are controlled by the Level 4 integrated Ridder Synopta system. Lighting and screen systems operate in concert throughout the day to maintain consistent light levels regardless of cloud cover or sunlight intensity.

IRRIGATION EQUIPMENT AND CONTROLS

The Greenhouse #1 drip irrigation system is controlled by the Level 4 integrated Ridder Synopta system, based upon measured relative humidity levels. As such, the schedule depending on greenhouse conditions and the consumption of the plants. The pumps serving the irrigation system are shown in Figure 42, with the dosing skid continuously pulling a hand-made fertilizer mixture into the irrigation stream.

Figure 42: Greenhouse #1 irrigation pump and dosing skid.

Source: ERI. 2024e.

Greenhouse #2

Figure 43: Flowering cannabis at Greenhouse #2.

Source: ERI. 2024e.

Greenhouse #2 is a 110-acre facility in Oxnard, California that grows cannabis, cucumbers, and tomatoes, as shown in Figure 43 above. This large growing area is divided into six greenhouses, each split into six or twelve zones of climate control.

The facility uses varying degrees of smart environmental controls to serve horticultural systems, as described in

Table 30.

Table 30: Levels of control by system at Greenhouse #2.

Environmental System	Level of Control
HVAC	Level 4 – integrated and intelligent control
Lighting	Level 2 – automated control
Irrigation	Level 4 – integrated and intelligent control

Source: ERI. 2024e.

The facility uses electricity from three sources: the grid, three onsite cogeneration plants, and four acres of dual-axis solar photovoltaic (PV) panels.

ENERGY ANALYSIS

Three cogeneration plants use natural gas to produce electricity and generate CO_2 and exhaust water, which is captured and reused within the facility. See Figure 44 below, which shows how the exhaust water is filtered in a condenser and pumped into three large heat storage tanks. The cold bottoms water is used to cool the cogeneration systems during the day, and hot overhead water is used to warm the greenhouses at night.

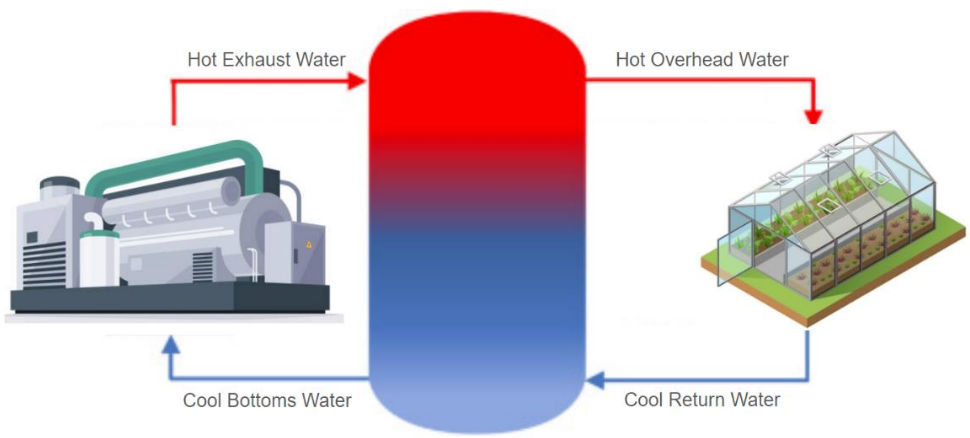

Figure 44: Cogen heat storage system.

Source: ERI. 2024f.

The onsite solar energy generation area is expansive, with four acres of panels installed. However, the operator notes several issues with the motor systems, as sections of solar panels do not rotate to capture the sun throughout the day. Greenhouse Farm #2 is planning on upgrading this system to improve the motor functionality, as well as install dual-sided panels to capture reflected solar radiation from the upward facing panel area.

Detailed monthly and annual data for this greenhouse corresponds with

Greenhouse B in the Energy Analysis section of this report.

HVAC EQUIPMENT AND CONTROLS

Greenhouse environmental conditions are maintained with hot and cold water from cogeneration heat storage tanks and a chiller; duct socks and fans provide ventilation, as shown in Figure 45 below. Large duct socks run below each of the benches. Airflow through the duct socks is controlled by 432 fans which line the east and west walls of the greenhouses (216 fans per wall), all of which are operated with VSDs. The greenhouse also operates shade curtains throughout all greenhouse areas using two 2000 Nm motors per greenhouse (Nm is a metric measurement of torque).

Figure 45: Duct socks and fans at Greenhouse #2.

Source: ERI. 2024e.

The pack house space dries the picked vegetation and is cooled by several packaged units, totaling 650 tons of chilling capacity. The space is divided into 14 drying rooms, each independently controlled by a central building automation system.

The Greenhouse #2 HVAC system is monitored with sensors throughout the greenhouse. There are four temperature sensors per greenhouse—two relative humidity (RH) and CO_2 sensors per greenhouse, and three temperature sensors per duct sock. HVAC equipment is controlled by a Priva control system to maintain target temperature and relative humidity setpoints, which integrates the Level 4 HVAC controls with the known operation of the irrigation system and forecasted weather data.

The Priva system also controls the greenhouse shade curtains in accordance with desired temperature and DLI. This light-harvesting controls strategy falls within Level 4 control, as it intelligently takes in forecasted weather conditions and current greenhouse conditions to change curtain operation to reach target DLI and temperature setpoints.

LIGHTING EQUIPMENT AND CONTROLS

The Greenhouse #2 flowering and vegetative greenhouse areas do not use supplemental horticultural lighting. The mother greenhouse areas operate 1-watt LED string lights which are automated using Level 2 timeclock controls. The facility is currently testing LED grow lights in propagation and vegetative areas to achieve more consistent canopy productivity, which are controlled via Level 2 photoperiod DLI controls. Both lighting systems are shown in Figure 46 below.

Figure 46: String lights LEDs undergoing testing at Greenhouse #2.

Source: ERI. 2024e.

IRRIGATION EQUIPMENT AND CONTROLS

All plants are irrigated using a drip irrigation system through the Level 4 Priva system. The control logic is a series of gravimetric-based PID loops, monitoring six plants on a six-foot-long scale for each valve in the facility. The system also collects and weighs the runoff water and measures the EC for the plants on the scale, and monitors EC and pH to control nutrient dosing.

The plants are watered in 50 mL shots at time increments of 40 to 60 minutes based upon sensor readings. The scale and valve system per row is shown in Figure 47.

Figure 47: Irrigation scale and valve system at Greenhouse #2.

Source: ERI. 2024e.

The Priva system can also access weather predictions and anticipate plant behavior for the following day. The facility has begun to monitor evapotranspiration rates through leaf temperature sensors as part of a research and development project, with the aim to include this reading in the Priva irrigation and HVAC logic.

Greenhouse #3

Figure 48: Greenhouse overview at Greenhouse #3.

Source: ERI. 2024e.

Greenhouse #3 in Salinas, California is a facility of 11 greenhouses, with a total area of 355,000 square feet. There are two distinct groups of greenhouses, designated North and South, as well as a small propagation area. The facility grows primarily cut roses, as well as strawberries, and until recently, cannabis, as shown in Figure 48 above.

The facility uses automated controls to serve the three major horticultural systems, described below in Table 31.

Table 31: Levels of control by system at Greenhouse #3.

Environmental System	Level of Control
HVAC	Level 2 – automated control
Lighting	Level 2 – automated control
Irrigation	Level 2 – automated control

Source: ERI. 2024e.

HVAC EQUIPMENT AND CONTROLS

HVAC systems serving the North and South Greenhouses consist of exhaust fans for cooling and steam unit heaters for heating, while small evaporative coolers and hot water unit heaters are used for propagation areas. The steam fan coils in the main greenhouses were equipped with over-bench flexible ducting to ensure even distribution of heating throughout the greenhouse, as shown in Figure 49. The North Greenhouses are equipped with motorized roof peak vents and the South Greenhouses are equipped with evaporative media along the interior corridor, which would allow them to be evaporatively cooled. However, the water drip piping to the media is not connected, and the evaporative cooling equipment is not currently used or functional.

Figure 49: Greenhouse #3 steam fan coil.

Source: ERI. 2024e.

Steam for the main greenhouses is generated by two 20,920 million Btu (MBtu) natural gas fired boilers, shown in Figure 50 below. Steam is produced at 45 pounds per square inch, and the boiler plant is equipped with a feedwater economizer. Hot water for the propagation area is generated by a 399 MBtu Raypak Xpak condensing boiler.

Figure 50: Greenhouse #3 steam boiler.

Source: ERI. 2024e.

All equipment is controlled by an older Priva Maximizer or a newer DGT brand LCC4 model control system, shown in Figure 51 below. For each zone, the control system controls all major systems including HVAC, lighting, and irrigation.

Figure 51: Environmental control system graphic user interface.

Source: ERI. 2024e.

While the DGT system does allow for a relatively high degree of automation, the facility operators are often frustrated with the inability of various systems to provide data and give feedback to one another. The Priva system is computer-based, but dated, and only allows for basic on-off control of integrated systems.

LIGHTING EQUIPMENT

Most greenhouse zones are not equipped with supplemental lighting as the crops do not need the additional PAR light. The greenhouse zones used for strawberries are equipped with both Philips LED fixtures, and contractor-style string lighting with BR-style LED lamps, as shown in Figure 52 below.

Figure 52: Greenhouse #3 strawberry zone supplemental lighting.

Source: ERI. 2024e.

The Philips LEDs are controlled by the DGT LCC4 control system, while the string lights are operated manually.

IRRIGATION EQUIPMENT AND CONTROLS

The irrigation system in both the North and South Greenhouses consists of 7.5 hp Baldor irrigation pumps equipped with VSDs, as shown in Figure 53 below. Nutrient dosing is also performed within the irrigation system and controlled by a Level 1, schedule-based iQ Pump Micro system. Figure 53 below shows the solenoid valves which control flow to individual greenhouse ranges. Irrigation is controlled for each zone by the Priva Maximizer or DGT LCC4 system.

Figure 53: Irrigation pump skid.

Source for both figures: ERI. 2024e.

Figure 54: Irrigation valves.

Appendix D: Field Demonstration Reports

Greenhouses L1 and L2

Figure 55: Greenhouses L1 and L2.

Source: ERI. 2025a.

This 682,070-square-foot lettuce facility has been in operation for over 25 years in Carpinteria, California. This site qualifies as HTR, both geographically and because it operated by non-English speakers.

The facility, which has varying levels of system automation, is composed of two buildings located across the street from each other: Greenhouse L1—at 76,270 square feet—for propagation and Greenhouse L2—at 163,200 square feet—for vegetative stage, as shown in Figure 55. Table 32 below describes the level of control by environmental system type.

Table 32: Field demonstration levels of control by system at Greenhouses L1 and L2.

Environmental System	Level of Control
Heating	Level 1 – basic control (for setpoints) Level 3 – integrated control (for valves and pumps)
Cooling & Dehumidification	Level 3 – integrated control
Lighting	Level 3 – integrated control
Irrigation	Level 3 – integrated control

Source: ERI. 2025a.

HVAC EQUIPMENT AND CONTROLS

The greenhouse uses a Priva automation system that controls most HVAC systems, shown in Figure 56 below.

Figure 56: Integrated environmental controls serving Greenhouses L1 and L2.

Source: ERI. 2025a.

Greenhouse curtain systems—blackout and shade curtains—are used to manage light levels received by crops during the day and reduce heat loss through the greenhouse coverings at night, as shown in Figure 57. The curtain systems are controlled by the Level 3 integrated control Priva automation system, which uses an algorithm that detects if greenhouse temperature, relative humidity, or PPFD light levels received by the plant canopy is outside of target environmental conditions and opens and closes curtains accordingly.

Figure 57: Greenhouse L1 curtain system.

Source: ERI. 2025a.

For heating, the greenhouse operation uses a hot water boiler system connected to bare under-bench heat pipes. The oldest boiler, shown in Figure 58, was installed in 2007. As of 2022, the boiler capacity was 6,142 MBH, but three new 4,000 MBH boilers were installed in 2023. The facility also uses a steam boiler that runs infrequently for sterilization of plants during propagation. The boiler setpoints are a Level 1 basic control and manually input at each boiler, while single-speed hot water pumps and heating valves are controlled by the Level 3 integrated control Priva system.

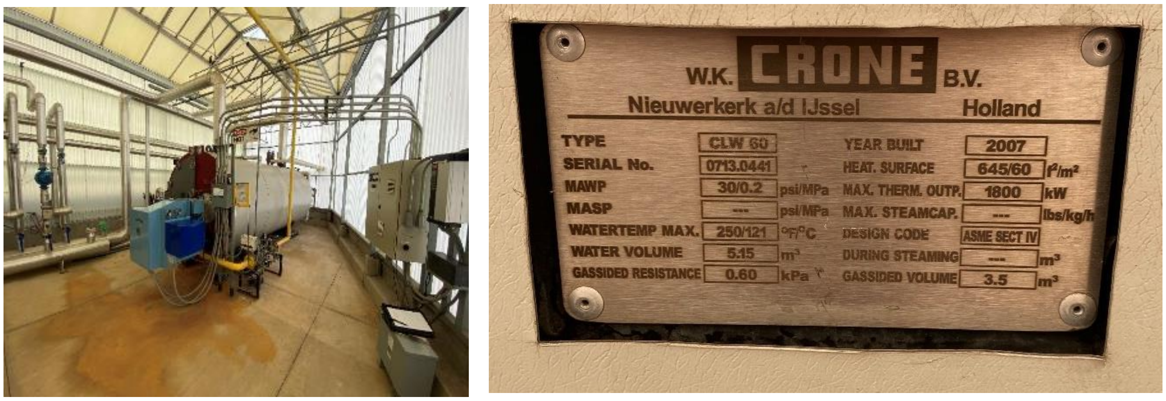

Figure 58: Greenhouse L1 and L2 boiler.

Source: ERI. 2025a.

For cooling and dehumidification, the greenhouse uses roof vents and horizontal airflow fans, shown in Figure 59. The fans do not have variable frequency drives and are controlled using the Level 3 integrated control Priva automation system. Greenhouse L1 uses 13 fans powered by two electrical circuit breakers, while Greenhouse L2 uses 11 fans powered by two breakers.

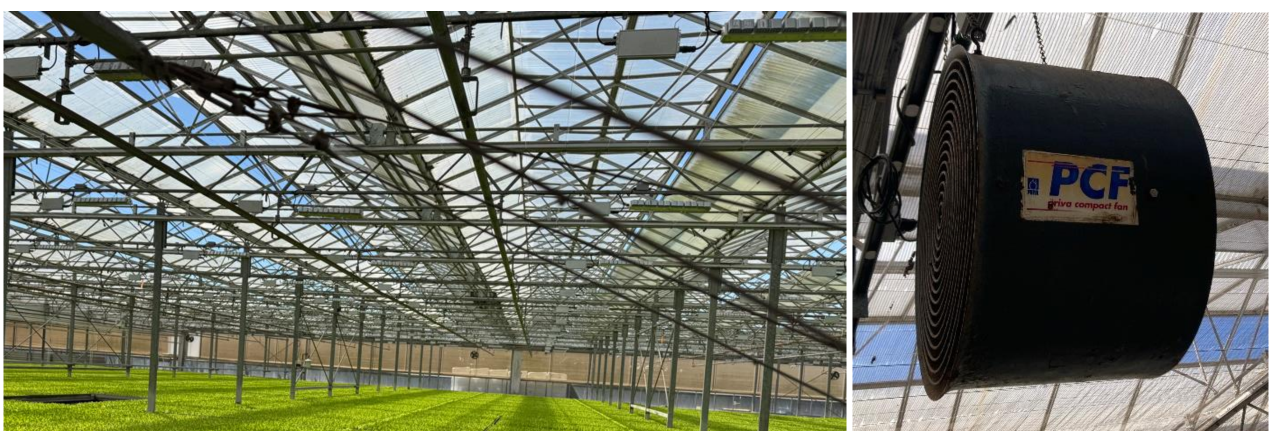

Figure 59: Horizontal airflow fans serving Greenhouses L1 and L2.

Source: ERI. 2025a.

LIGHTING EQUIPMENT AND CONTROLS

The propagation greenhouse, Greenhouse L1, uses 392 LED supplemental light fixtures powered by 14 electrical circuit breakers. The vegetative greenhouse, Greenhouse L2, uses 665 high-pressure sodium supplemental light fixtures powered by 32 breakers, as shown in Figure 60.

Figure 60: High-pressure sodium supplemental lighting serving Greenhouse L2.

Source: ERI. 2025a.

Prior to the field demonstration installation, one zone of Greenhouse L1 had a photosynthetically active radiation (PAR) sensor sharing data on actual light levels received at the plant canopy with the Priva automation system. All horticultural lighting at Greenhouses L1 and L2 is controlled by the Level 3 integrated control Priva system. The lights are scheduled to turn on between 2:00 a.m. and 7:00 a.m. to provide the plant canopy with a target DLI of 19 μmol/m^2/day.

IRRIGATION EQUIPMENT AND CONTROLS

The irrigation pumps are not equipped with variable frequency drives; rather, irrigation equipment like the irrigation booms shown in Figure 61 are controlled by the Priva automation system.

Figure 61: Irrigation Systems Serving Greenhouse L1

Source: ERI. 2025a.

FIELD DEMONSTRATION SCOPE

Two field demonstrations of smart monitoring equipment were installed at Greenhouses L1 and L2 to explore the energy savings of smart controls strategies applied to horticultural lighting and fan systems, shown below in Figure 62.

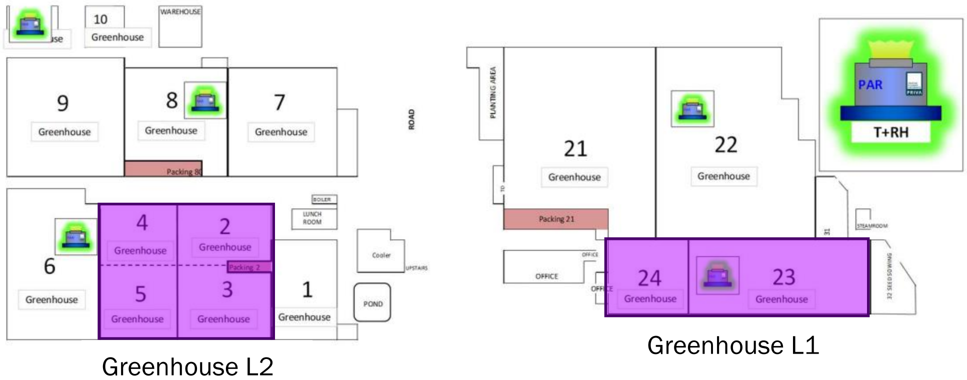

Figure 62: Field demonstration scope at Greenhouses L1 and L2.

Source: ERI. 2025a.

Within each greenhouse, the research team compared one highly instrumented and one less instrumented zone. In Greenhouse L1, zones 23 and 24 were compared; in Greenhouse L2, zones 2 and 3 were compared against zones 4 and 5. All zones received system-level circuit monitoring, shown in the left image of Figure 63. The highly instrumented zone received more climate sensing hardware, like the PAR sensors pictured Figure 63’s right image.

Figure 63: Field demonstration scope at Greenhouses L1 and L2.

Source: ERI. 2025a.

BUSINESS BENEFITS

The grower was interested in participating in the field demonstration to get a better understanding of the energy consumed by their horticultural process systems. While the greenhouses have integrated controls for many environmental systems, energy is not monitored at the system level. The leadership team felt that if energy data could demonstrate how expensive older systems are to operate, business cases for capital plans could be more easily quantified.

Greenhouse L1 and L2 leadership and grower teams expressed interest in implementing behavioral changes based on recommendations from the energy monitoring system dashboard.

LESSONS LEARNED

From October 2024 to May 2025, the research team documented issues and resolutions to identify field demonstration deficiencies, meeting with the Greenhouse L1 and L2 teams. The following lessons learned could shape program recommendations:

1. The grower's existing lighting, HVAC, and irrigation control systems provided a high level of sophistication but did not report energy use at the system level.
2. The existing control systems do not utilize machine learning, cameras, and sensing technology to optimize resources like water, fertilizer, and electricity use and demand. Their primary function is to optimize plant health.
3. The IT team was not sufficiently informed about the infrastructure for the field demonstration and required implementation of security protocols for smart controls hardware integration and connection to the greenhouses' internal corporate network. A dedicated gateway was provided to give internet access to the field demonstration energy monitoring equipment, but some hardware was not allowed to be installed, such as cameras.
4. The corporate leadership team and the operations team of growers each had staff turnover during the six-month field demonstration, creating communication breakdowns and a low interest in resolving field demonstration issues identified, such as replacing batteries on sensors. This made remote access to the energy monitoring dashboard a critical asset throughout the field demonstration period.

BARRIERS TO EFFICIENCY

Accelerating the adoption of integrated and intelligent controls systems with energy monitoring at greenhouses like Greenhouse L1 and L2 may be challenging for EE programs for the following reasons:

- Large leafy greens growers have more critical priorities than managing energy use, like retaining skilled labor, managing labor costs, managing production costs, and maintaining crop quality.
- The business priorities for sustainability and EE projects may ebb and flow.
- Staff resources that can be focused on EE may not exist or likely will not be consistently engaged.
- Staff turnover makes remote access increasingly important for program energy savings measurement and verification.
- Smart automation hardware must navigate corporate IT security requirements that larger growers are more likely to implement.

Greenhouse F

Figure 64: Greenhouse F.

Source: ERI. 2025a.

Greenhouse F, pictured in Figure 64 above, is a 650,000-square-foot orchid-growing facility in Salinas, California. This site qualifies as HTR both geographically and because it is operated by non-English speakers.

The greenhouse spaces are zoned into two main areas: a 540-foot-by-650-foot "cool" space, and a 200-foot-by-650-foot "hot" space, with additional areas used for packaging, offices, and mechanical equipment. The field demonstration occurred in the "hot" space of Greenhouse F.

The growing spaces are equipped with automated cranes and sliding benches, which are used to move plants between the "cool" and "hot" spaces depending on their growth stage. Greenhouse F has an integrated automation system, which controls all horticultural systems, including heating, cooling, irrigation, and fogging/humidification, but does not monitor system-level energy consumption. Table 33 below describes the level of control by environmental system type.

Table 33: Field Demonstration levels of control by system at Greenhouse F.

Environmental System	Level of Control
Heating	Level 1 – manual control (for setpoints) Level 3 – integrated control (for heating valves and pumps)
Cooling & Dehumidification	Level 2 – automated control (for fogger) Level 3 – integrated control (for other HVAC including curtains)
Lighting	Level 3 – integrated control
Irrigation	Level 3 – integrated control

Source: ERI. 2025a.

HVAC EQUIPMENT AND CONTROLS

The greenhouse uses a Hortimax automation system that controls most HVAC systems, as shown in Figure 65.

Figure 65: Integrated environmental controls serving Greenhouse F.

Source: ERI. 2025a.

For cooling and dehumidification, the greenhouse uses roof vents and horizontal airflow fans, as shown in the left image of Figure 66. Greenhouse curtain systems are used to manage light levels received by crops during the day and reduce heat loss through the greenhouse coverings at night, shown in the left image of Figure 66. The curtain systems are controlled by the Level 3 integrated control Hortimax automation system, using an algorithm that detects if greenhouse temperature, relative humidity, or PPFD light levels received by the plant canopy is outside of target environmental conditions and opens and closes curtains accordingly. Greenhouse F also uses a fogger system that is controlled separately using factory controls, shown in the right image of Figure 66.

Figure 66: Greenhouse F greenhouse HVAC systems.

Source: ERI. 2025a.

For heating, the greenhouse operation uses two forced draft hot water boilers connected to a plate-type heat exchanger and distributes heat through bare under-bench heat pipes. Both boilers, shown in Figure 67, were manufactured in 2010 and as of 2025, have a combined boiler capacity of 49,135 MBH. The boiler setpoints are a Level 1 basic control and manually input at each boiler, while the single-speed 0.13 kW hot water pumps and heating valves are controlled by the Level 3 integrated control Hortimax system.

Figure 67: Greenhouse F boilers.

Source: ERI. 2025a.

LIGHTING EQUIPMENT AND CONTROLS

Greenhouse F does not use supplemental horticultural lighting.

IRRIGATION EQUIPMENT AND CONTROLS

Irrigation pumps are constant speed and are not equipped with variable frequency drives. The irrigation and fertigation, or nutrient dosing, equipment shown in Figure 68 is controlled by the Level 3 integrated control Hortimax automation system.

Figure 68: Irrigation and fertigation systems serving Greenhouse F.

Source: ERI. 2025a.

FIELD DEMONSTRATION SCOPE

One field demonstration of smart monitoring equipment was installed at Greenhouse F to explore the energy savings of smart controls strategies applied to horticultural fan and heating pump systems, seen in Figure 69. The field demonstration was performed in the hot side of the greenhouse (shaded purple).

Figure 69: Field demonstration scope at Greenhouse F.

Source: ERI. 2025a.

Within the greenhouse, the research team compared a highly instrumented zone and a zone with less instrumentation.

BUSINESS BENEFITS

The grower was interested in participating in the field demonstration to see additional greenhouse climate data, especially at different elevations than their existing climate sensors. Additional sensors were placed below benches and above greenhouse curtains.

Greenhouse F leadership and grower teams indicated a strong willingness to update controls strategies based on data collected in the field demonstration.

LESSONS LEARNED

From December 2024 to May 2025, the research team documented issues and resolutions to identify field demonstration deficiencies, meeting with the Greenhouse F team. The following lessons learned could shape program recommendations:

1. The grower's existing HVAC and irrigation control systems provided a high level of sophistication but did not report energy use at the system level.
2. The existing control systems do not utilize machine learning, cameras, and sensing technology to optimize resources like water, fertilizer, and electricity use and demand. Their primary function is to optimize plant health.
3. The electrical loads from end-uses in the heated greenhouse were lower than anticipated. Some electrical loads were not feasible to monitor, due to sporadic and short equipment runtimes.

4. Grower team buy-in is a key factor for successful installation and implementation of smart monitoring/controls equipment and strategies. Growers were excited about gaining additional data visibility on greenhouse conditions to use to improve plant health. Saving energy and money would be a strong secondary motivator, but cannot come at the cost of plant health.

BARRIERS TO EFFICIENCY

Accelerating the adoption of integrated and intelligent controls systems with energy monitoring at greenhouses like Greenhouse F may be challenging for EE programs for the following reasons:

- Floriculture growers use less energy-intensive systems and may not use supplemental lighting; these operations are better candidates for pump and fan VFD and motor control EE projects.
- California floriculture operations may be part of a network of greenhouses owned by an international corporation so getting buy-in for adopting energy-saving controls hardware and software can take time for multiple levels of leadership buy-in.
- Staff resources that can be focused on EE may not exist or likely will not be consistently engaged.
- While larger greenhouses provide opportunities for higher volume energy savings through control optimizations, they are generally risk-averse, and likely have existing equipment and controls with some degree of automation, along with existing vendor and manufacturer relationships and contracts.

Indoor Farm M

Figure 70: Indoor Farm M.

Source: ERI. 2025a.

Indoor Farm M operates a 1,050-square-foot edible mushroom grow facility in Eureka, California. This site qualifies as HTR because it is geographically HTR, as well as a microbusiness and a low energy user.

The facility consists of three main areas: a 20-foot-by-30-foot laboratory building where initial mushroom cultures, or spawn, are developed; a 15-foot-by-15-foot incubation room, where growing media is sterilized, the spawn cultures are introduced to the media, and mycelium is allowed to develop; and a 15-foot-by-15-foot grow room, where the mycelium is introduced to fresh air, which allows the edible fruiting mushroom bodies to develop. Indoor Farm M did not have an integrated controls system prior to participation in the field demonstration; all systems were controlled independently, either manually or with simple thermostats or timers.

Indoor Farm M has an integrated and intelligent automation system which controls all indoor farming systems, including heating, cooling, irrigation, and fogging/humidification and monitors system-level energy consumption.

Table 34 describes the level of control by environmental system type.

Table 34: Field demonstration levels of control by system at Indoor Farm M.

Environmental System	Level of Control
Heating	Level 1 – basic controls
Cooling & Dehumidification	Level 0 – manual controls
Lighting	Level 0 – manual controls
Irrigation	N/A

Source: ERI. 2025a.

HVAC EQUIPMENT AND CONTROLS

The greenhouse uses a Microclimates automation system that controls all HVAC systems shown in Figure 71.

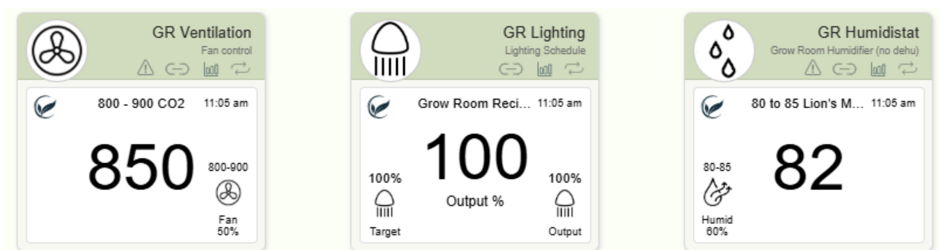

Figure 71: Graphic user interface for integrated environmental controls serving indoor Farm M grow room.

Source: ERI. 2025a.

The grow room does not have heating or mechanical cooling systems. There is a ventilation fan that operates on a timer to maintain low CO_2 levels, and a humidifier controlled by a mechanical humidistat to maintain the required relative humidity of 80 to 85 percent RH.

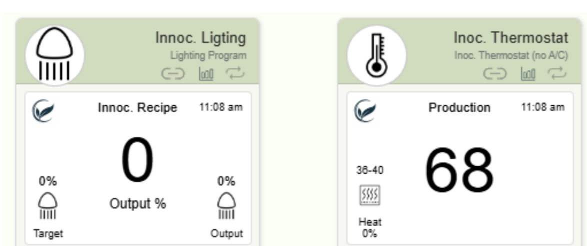

Figure 72: Graphic user interface for integrated environmental controls serving Indoor Farm M inoculation room.

Source: ERI. 2025a.

The inoculation room is equipped with a portable space heater that is operated manually. Ventilation is operated manually when the room is occupied but left off at other times since low CO_2 levels promote fruiting body (mushroom) development. The laboratory is equipped with three portable space heaters which operate independently, controlled by thermostats.

LIGHTING EQUIPMENT AND CONTROLS

Indoor Farm M does not use horticultural lighting since mushrooms are not crops that develop using photosynthesis. The inoculation room is equipped with lighting control timers that are used during the development of some mushroom varieties. Lighting operates on timers in the grow room and is operated manually in other spaces most of the time.

IRRIGATION EQUIPMENT AND CONTROLS

Mushroom farms do not use irrigation equipment since the crop is grown in spawn blocks that are kept moist using the humidity in the air.

FIELD DEMONSTRATION SCOPE

One field demonstration of smart monitoring equipment was installed at Indoor Farm M to explore the energy savings of smart controls strategies applied to horticultural fan and heating pump systems, as shown in Figure 73. The field demonstration was performed in the hot side of the greenhouse (shaded purple).

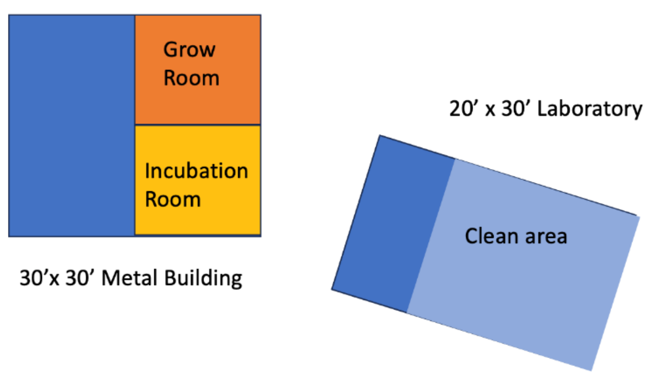

Figure 73: Field demonstration scope at Indoor Farm M.

Source: ERI. 2025a.

Within the farm, the project team compared the incubation room and the grow room.

BUSINESS BENEFITS

The grower was interested in participating in the field demonstration to eliminate manual control and advance to integrated control for all farming systems.

Indoor Farm M ownership was interested in learning new controls strategies to save energy based on data collected in the field demonstration.

LESSONS LEARNED

From December 2024 to May 2025, the project team documented issues and resolutions to identify field demonstration deficiencies, meeting with the Greenhouse F team. The following lessons learned could shape program recommendations:

1. It can be easier to get grower buy-in with smaller growers for the implementation of smart controls equipment and strategies.
2. Smaller facilities with more basic existing controls are more likely to see smart controls systems as a substantial upgrade and will be more agile and willing to experiment with controls strategies to improve operational efficiencies.
3. Mushroom growers are a unique type of CEA facility that can be all-electric.
4. Mushroom farms use unique horticultural process systems and controls savings at these facilities will come from HVAC equipment above any other system.

BARRIERS TO EFFICIENCY

Accelerating the adoption of integrated and intelligent controls systems with energy monitoring at indoor farms like Indoor Farm M may be challenging for EE programs for the following reasons:

- Some CEA facilities are located in HTR areas and will require a higher level of effort for program outreach.
- Small farms may not produce cost-effective energy savings for a smart CEA environmental controls EE program.
- Mushroom farm energy consumption from HVAC and other process systems is low and may not be a cost-effective CEA customer for a smart CEA environmental controls EE program.

Appendix E: Greenhouse DLI Controls Savings Calculations

74 is a screenshot of the study's custom energy savings calculator.

Free Input
Dropdown Input
Outputs

Climate Zone	CZ01	
Facility Square Feet	10,000	
Facility Glazing VLT	0.7	
Crop	Tomato	

Lighting Controls

Estimated Fixture Quantity	179	
Fixture Quantity (Override)		
Light Fixture Wattage	600	W
System Size	107	kW
Fixture Efficacy	2.8	umol/J
System PPFD	322.9	umol/s*m2
Photoperiod	12	
Estimated DLI Target	16	mol/m2*day
DLI Target (Override)		mol/m2*day

Figure 74: DLI controls energy savings calculator inputs and outputs.

Source: ERI. 2025b.

Table 35 describes assumptions that influence the energy savings estimate for greenhouse DLI controls.

Table 35: Greenhouse leafy greens DLI controls measure savings potential.

Crop Type	Photoperiod (hours)	Average Lit Area (ft^2 per light)	DLI Target (mol/m^2-day)
Cannabis - Flower	12	20	43.2
Cannabis - Veg	18	24	38.9
Leafy Greens	18	58	17
Tomato	12	56	16

Source: CEC. 2024b.

Table 36 through Table 39 describe the estimated electricity consumption and demand savings for Daily Light Integral (DLI) controls for leafy greens, tomato, cannabis (vegetative), and cannabis (flowering) greenhouses for each of the 16 California CZ for a 10,000 sq ft greenhouse with a glazing visible light transmittance (VLT) of 0.7.

Table 36: Greenhouse leafy greens DLI controls measure savings potential.

California Climate Zone (CZ)	Average Electricity Savings (kWh)	Average % Savings	Average Demand Reduction (kW)	Average Area-Normalized Electricity Savings (kWh/ft^2)
CZ01	403,227	59%	46	40
CZ02	431,340	63%	49	43
CZ03	429,859	63%	49	43
CZ04	432,167	64%	49	43
CZ05	432,578	64%	49	43
CZ06	433,986	64%	50	43
CZ07	435,019	64%	50	44
CZ08	434,054	64%	50	43
CZ09	432,995	64%	49	43
CZ10	433,893	64%	50	43
CZ11	423,500	62%	48	42
CZ12	432,979	64%	49	43
CZ13	433,601	64%	49	43
CZ14	440,470	65%	50	44
CZ15	438,579	65%	50	44
CZ16	437,066	64%	50	44

Source: ERI. 2025b.

Table 37: Greenhouse tomato DLI controls measure savings potential.

California Climate Zone (CZ)	Average Electricity Savings (kWh)	Average % Savings	Average Demand Reduction (kW)	Average Area-Normalized Electricity Savings (kWh/ft^2)
CZ01	313,803	67%	36	31
CZ02	361,391	77%	41	36
CZ03	357,416	76%	41	36
CZ04	362,641	77%	41	36
CZ05	364,591	78%	42	36
CZ06	366,978	78%	42	37
CZ07	370,718	79%	42	37
CZ08	369,296	79%	42	37
CZ09	367,691	78%	42	37
CZ10	370,792	79%	42	37
CZ11	350,075	75%	40	35
CZ12	365,440	78%	42	37
CZ13	368,701	79%	42	37
CZ14	382,037	81%	44	38
CZ15	381,520	81%	44	38
CZ16	376,334	80%	43	38

Source: ERI. 2025b.

Table 38: Greenhouse cannabis (vegetative) DLI controls measure savings potential.

California Climate Zone (CZ)	Average Electricity Savings (kWh)	Average % Savings	Average Demand Reduction (kW)	Average Area-Normalized Electricity Savings (kWh/ft^2)
CZ01	850,701	52%	97	85
CZ02	926,149	56%	106	93
CZ03	939,225	57%	107	94
CZ04	953,020	58%	109	95
CZ05	953,539	58%	109	95
CZ06	956,789	58%	109	96
CZ07	959,693	58%	110	96
CZ08	960,065	58%	110	96
CZ09	958,706	58%	109	96
CZ10	964,662	59%	110	96
CZ11	928,557	57%	106	93
CZ12	957,029	58%	109	96
CZ13	960,453	58%	110	96
CZ14	991,749	60%	113	99
CZ15	985,315	60%	112	99
CZ16	974,277	59%	111	97

Source: ERI. 2025b.

Table 39: Greenhouse cannabis (Flowering) DLI controls measure savings potential.

California Climate Zone (CZ)	Average Electricity Savings (kWh)	Average % Savings	Average Demand Reduction (kW)	Average Area-Normalized Electricity Savings (kWh/ft^2)
CZ01	523,745	40%	60	52
CZ02	611,102	47%	70	61
CZ03	668,118	51%	76	67
CZ04	694,623	53%	79	69
CZ05	703,674	54%	80	70
CZ06	699,015	53%	80	70
CZ07	709,626	54%	81	71
CZ08	711,020	54%	81	71
CZ09	711,014	54%	81	71
CZ10	723,124	55%	83	72
CZ11	655,969	50%	75	66
CZ12	700,481	53%	80	70
CZ13	706,049	54%	81	71
CZ14	770,523	59%	88	77
CZ15	756,791	58%	86	76
CZ16	733,016	56%	84	73

Source: ERI. 2025b.

Appendix F: Greenhouse Ventilation Fan VFD Savings Calculations

Figure 75 is a screenshot of the study's custom energy savings calculator.

Free Input
Dropdown Input
Outputs

Climate Zone	CZ01	
Facility Square Feet	10,000	
Facility Glazing VLT	0.7	
Crop	Tomato	

HVAC Controls

Fan Quantity	20	
Fan Horsepower	1.5	hp
Fan System Size	22.371	kW
Heating Setpoint	68	°F

Fan Energy Savings	164,410.90	kWh
% Savings	84%	
Average Demand Reduction	18.77	kW
Area-Normalized Savings	16.4	kWh/sqft

Figure 75: Greenhouse ventilation fan VFD energy savings calculator inputs and outputs.

Source: ERI. 2025b.

Table 40 describes the estimated electricity consumption and demand savings for greenhouse ventilation fan VFD controls for each of the 16 California CZ for a 10,000 sq ft greenhouse with (20) 1.5-horsepower ventilation fans controlled to a 68 °F heating setpoint.

Table 40: Greenhouse ventilation fan VFD measure savings potential.

California Climate Zone (CZ)	Average Electricity Savings (kWh)	Average % Savings	Average Demand Reduction (kW)	Average Area-Normalized Electricity Savings (kWh/ft²)
CZ01	164,411	84%	19	16
CZ02	142,506	73%	16	14
CZ03	149,421	76%	17	15
CZ04	131,798	67%	15	13
CZ05	143,410	73%	16	14
CZ06	136,821	70%	16	14
CZ07	125,284	64%	14	13
CZ08	115,584	59%	13	12
CZ09	116,433	59%	13	12
CZ10	108,934	56%	12	11
CZ11	110,333	56%	13	11
CZ12	118,127	60%	13	12
CZ13	104,129	53%	12	10
CZ14	106,728	54%	12	11
CZ15	81,816	42%	9	8
CZ16	117,743	60%	13	12

Source: ERI. 2025b.

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