RESOURCE INNOVATION INSTITUTE

Best Practices Guide Lighting

for Controlled Environment Agriculture (CEA) Operations

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A Best Practices Guide for Lighting Programs

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In Partnership with

ACEEE American Council for an Energy-Efficient Economy

USDA United States Department of Agriculture Natural Resources Conservation Service

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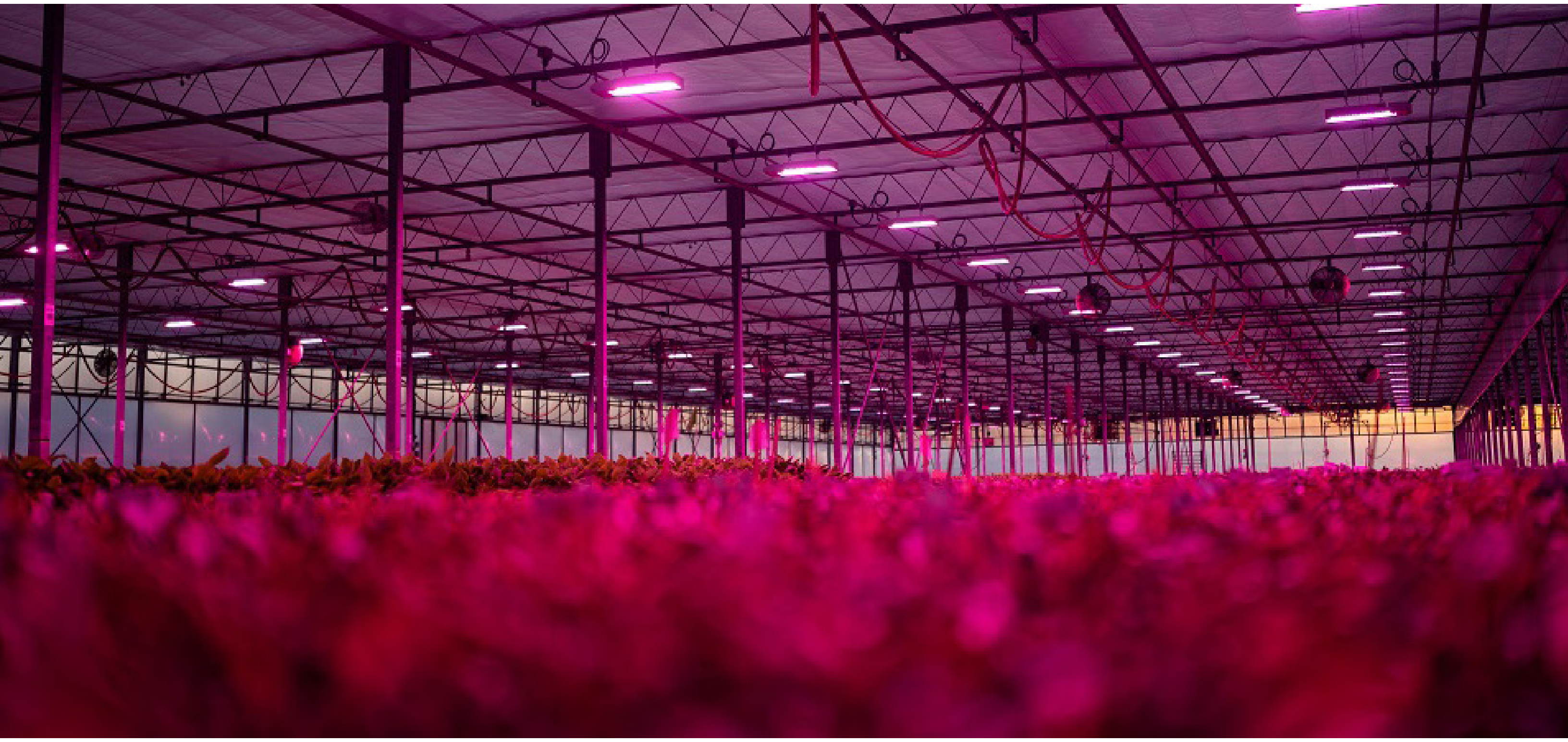
Overview



As a producer operating in a constantly evolving industry, **you may feel like it is hard to know who to trust.** The controlled environment agriculture (CEA) market is dynamic, technology is advancing, and there are complex terms to know for every strategy. It can be hard to navigate the design and construction process and challenging to understand how to plan a highly productive and resource-efficient facility.

We are here to help. As an objective, data-driven non-profit organization, Resource Innovation Institute measures, verifies and celebrates the world's most efficient agricultural ideas. Our peer-reviewed Best Practices Guides are a way of helping growers like you understand the most resource-efficient technologies and how to use them to boost your bottom line.

The operational changes necessary for an efficient food or floriculture facility may be detailed, but **it does not have to be a mystery.** Our membership is composed of subject matter experts with the knowledge to help you build and operate the most high-performance and cost-effective facility for cultivating plant life in controlled environments.

You may be looking for a **source of reliable third-party information,** motivated to reduce overhead for your business, or have goals for a more resource-efficient facility. Whatever the reason, when you are considering a decision related to the systems used in your facility, we hope you lay the groundwork with the insights offered in Resource Innovation Institute's Best Practices Guides.

INPUT from industry leaders and partners → RESOURCE INNOVATION INSTITUTE → **EDUCATION** and advocacy about best practices for growers

COVER IMAGE : VERTICAL HARVEST FARMS; THIS PAGE: SIGNIFY, WALTERS GARDENS

Purpose

Any grower can turn on a light, but operating lighting for cultivation applications can be an art, while using lighting equipment efficiently can be a science.

The purpose of this CEA Lighting Best Practices Guide is to support you, the cultivator, and your design, construction, and operations professionals:

- Speak the language of horticultural lighting
- Review manufacturer's literature to evaluate your purchasing options
- Understand crucial considerations when selecting horticultural lighting
- Maximize incentives for energy-efficient lighting solutions
- Install and operate successful lighting solutions in alignment with your business model

Demystify Terms

Throughout this guide, you will learn key terms related to optimizing the design and construction of lighting systems for food and floriculture for plant growth and development. Greenhouses are planned and built differently than indoor farms and use lighting equipment differently to maintain desired conditions.

This guide is intended to serve producers and their partners seeking to optimize controlled environments for cultivating food and floriculture crops. CEA project partners may include architects, engineers, hardware manufacturers, suppliers, systems integrators, data aggregators, controls contractors, commissioning agents, and utility and efficiency program energy engineers.

Throughout this guide, you can learn about key terms related to horticultural lighting, their units of measurement and how they are used, why the terms are important to you as a cultivator, and how the terms may be commonly misunderstood or misapplied.

The key terms address the topical areas listed below:

- Cultivation
- Energy & Power
- Horticultural Lighting
- Cultivation Key Performance Indicators (KPIs)

Consult our online glossary of key CEA lighting terms to expand your horticultural lighting vocabulary.

PHOTO : ROB EDDY, PURDUE UNIVERSITY

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To learn about how to effectively design and build CEA facilities, consult our *Facility Design & Construction Best Practices Guide for Controlled Environment Agriculture (CEA)*. To understand the interactive effects between your lighting and HVAC systems, check out our *HVAC Best Practices Guide for Controlled Environment Agriculture (CEA)*, which covers the heating, ventilation, air conditioning, and dehumidification terms and systems used for cultivation environments. To effectively automate your lighting, HVAC, and controls systems, check out our *Controls & Automation Best Practices Guide for Controlled Environment Agriculture (CEA)* publishing in July 2022.

SECTION

01

Optimize Lighting for CEA Facilities

PHOTO: SIGNIFY, CANADIAN VALLEY

In horticulture applications, lighting choices impact crop yields and product quality. Applying lighting solutions in diverse facility types can necessitate different technology choices and upfront costs impact greenhouse and indoor producers differently. It is crucial to maximize your return on investment for horticultural lighting systems, as this equipment can be in the top 50% of capital expenditures for CEA facility construction costs. Table 1 below offers some ranges in capital costs for CEA lighting systems by facility type and crop lighting needs. The higher end of the ranges represent costs for more efficient systems lighting crops requiring more light.

Table 1: Capital Costs for CEA Lighting Systems

	Costs for Greenhouse Supplemental Lighting ($USD)	Costs for Indoor Vertical Sole-Source Lighting ($USD)
Crops with Lower Lighting Needs	$20 - 45 per canopy sq ft	$25 - 45 per canopy sq ft
Crops with Higher Lighting Needs	$20 - 80 per canopy sq ft	$70 - 100 per canopy sq ft

Sub-optimal performance of lighting systems can hurt your competitive advantage. There are diverse strategies and many types of equipment you can use to accomplish your goals. Understanding the process application for facility systems equipment enables growers to choose efficient lighting products to reduce energy use and operating costs.

Utilities want to incentivize adoption of emerging technologies, and lighting is a key system in CEA facilities supported by efficiency programs. To ensure lighting systems achieve their energy savings potential, efficiency programs also offer technical assistance during design, installation, and operation. To offset the first cost of high-performance lighting equipment, CEA producers can receive financial help to buy down efficient lighting products.

Standards for safety, efficacy, and quality help ensure the technology you install is built to last on your farm. Over the years, you may have used a few different types of lighting options, from HID (High Intensity Discharge) to LED. Today's horticultural LED market offers a wide variety of solutions suited to best fit the needs of CEA producers.

Third-party verified LED lighting solutions can optimize crop productivity and facility efficiency. Qualified product libraries maintained by certification organizations give you the information you need to judge the energy performance and durability of hundreds of options that have met technical performance requirements.

Regulations for energy performance have emerged in some regions that affect greenhouses and indoor farms. Cultivators everywhere can benefit from understanding how LED lighting can be a tool for facility compliance and operational success. Greenhouses and vertical farms have different lighting needs and create diverse impacts. Facility operators and their project partners can work together to minimize environmental impacts like light pollution and high energy demands.

Resilient producers plan for competition by managing operational energy and improving resource efficiency. Models for production and associated resource consumption differ by facility type and location. In the following sections, you will learn how lighting systems in CEA facilities affect your plants and support productivity, profitability and optimized conditions for plant growth and development. Understanding the terms used to describe your indoor grow environment requires a slight learning curve but is essential if you want to ask informed questions, make informed business decisions, and achieve a resource-efficient and high-performance operation.

Benefits of Using LED Lighting in CEA Facilities

LED horticultural lighting offers diverse benefits for plants, producers, and CEA facilities. In the past five years, hundreds of products developed specifically for plant growth and development have become more available and less expensive, while efficiency programs have increased their support with financial incentives.

Save Energy - LED solutions can demand less energy than traditional lighting solutions like high-pressure sodium (HPS), metal halide (MH), or fluorescent (T-type) light fixtures. LEDs can save even more on utility bills if operated to avoid certain times of the day when demand is at electric grid capacity (peak hours). Table 2 below describes the diverse technology that can support substantial energy savings in indoor farms and greenhouses. Energy-saving lighting technology can receive incentives from utility efficiency programs.

Table 2: Energy Savings Potential of LED Lighting Technology

Energy-Saving Lighting Solutions	Energy Savings Potential[1]
Horticultural Lighting Systems[2]: • Air-cooled LED light fixtures • Liquid-cooled LED lighting systems • LED lamps • Lighting controls	30 - 40%

Affect HVAC Sizing - Facilities running LED lighting systems can have lower heat loads than facilities using HID lighting systems. LED fixtures can give off less heat, which affects HVAC capacity needed to maintain target environmental conditions in your greenhouse or indoor farm. Lower heat output from lighting can be a bigger benefit for indoor farms than for greenhouses, which generally need more heat and may use lights as a heat source. Lower HVAC loads mean that your facility's HVAC system capacity can be reduced, depending on the types of equipment used for heating, cooling, and dehumidification. Downsizing HVAC equipment can result in up to 33% lower capital costs and help fund higher upfront costs of LED lighting systems[3]. Smaller HVAC equipment can also reduce recurring operating costs for environmental management. LED approaches also can avoid wide temperature and humidity swings within your cultivation spaces between ‘lights on’ and ‘lights off’ periods.

Operate Differently - LEDs can be mounted closer to your crop canopy and can provide higher light intensities with better uniformity. This means you can grow using vertical farming approaches more easily. Due to higher photon efficacy, target light levels can be met with fewer fixtures, freeing up capital for other investments. With LED lighting solutions and dimming controls, your HVAC system can also minimize short-cycling. Short-cycling is hard on your HVAC equipment and will reduce its useful life.

Plug and Play - LED light fixtures have no bulbs, and instead have boards of diodes. Boards can be customized with light recipes to provide a specific mix of spectra, and some fixtures can change spectral distribution with controls. LEDs can be cycled on and off and ramped up and down easily and with precise granularity. LED fixtures capable of dimming from 1 - 100% can provide your crop canopy with exactly as much light as they need.

Steer Crops - LEDs provide adequate light levels and specialized light recipes for plants. Plants grown with

1 Controlled Environment Agriculture Market Characterization Report: Supply Chains, Energy Sources and Uses, and Barriers to Efficiency, RII, 2021.
2 LED Lighting Best Practices Guide for Cannabis Cultivation, RII, 2019.
3 Opportunities in Controlled Environment Agriculture, Commonwealth Edison, 2021.

LEDs can produce similar or better yields than those grown with other lighting technology. Lighting systems operated with customized and/or tunable spectra can improve crop quality. Spectral treatments only possible with LED can impact taste, structure, and pigments of fruits and can help with pathogen management, and have positive impacts on harvested yield.

Depend on Durability - LED light fixtures can maintain light output for longer than traditional lighting solutions like HID. Technology manufacturers influence the quality of fixture design and construction, which can affect the useful lifetime of their product. LED fixtures can be rated for ingress protection (IP), which means they are vapor tight. Safely apply sprays for integrated pest management and hose down fixtures for cleaning.

How CEA Facilities Use Light

The strategies for lighting CEA facilities depend on how much light crops need and the types of light the facility can use for crop growth. Three major styles of CEA cultivation drive horticultural lighting decisions. For every stage and style of cultivation, there is a high-performance lighting solution and controls strategy.

Cultivation Approach - Greenhouses and indoor farms may value the benefits of LED horticultural lighting differently based on production goals. The three most common CEA cultivation approaches have different pros and cons in regards to lighting. Greenhouses use sunlight as the primary source of light for plant growth and development. Depending on the crop being grown and greenhouse location and construction, *supplemental lighting* solutions are used to meet lighting requirements to optimize quality and yield. High-wire greenhouses may use *toplighting* and *intracanopy* lighting to increase yields of vine crops. Indoor farms use *sole-source lighting* solutions to meet all crop needs and depend on electric light fixtures to drive photosynthesis. Vertical cultivation approaches incorporate tiers of racks to toplight crops. CEA facilities growing flowering crops can use *photoperiod lighting* to trigger plant responses to day and night.

This document starts with key concepts that apply to all three cultivation methods – and then examines what makes these concepts vary when applied differently in vertical indoor and greenhouse environments.



PHOTOS FROM LEFT: GRETCHEN SCHIMELPFENIG, UNIVERSITY OF VERMONT; ROB EDDY; GRETCHEN SCHIMELPFENIG, UNIVERSITY OF VERMONT

How CEA Crops Use Light

Lighting is a mission-critical system in CEA facilities that must meet the needs of your crops. The needs of CEA crops are unique and affected by cultivation approach. Understand how light spectrum and light distribution affect crop development and morphology. Not all photons and light fixtures are created equal.

Understand Inputs - Light is the primary influencer of plant vitality and yield and can affect the development of fungi. Plants and fungi harness light as an energy source and use photons from different parts of the spectrum differently. Light has at least two major roles for plants: *photosynthesis* - and also as important - setting a stage for photosynthesis. Proper development of the chloroplast, optimized stature, morphology, maintenance of the chloroplast are all dictated by light through photosensors and are separate. Light shapes the machinery that makes plants go.

Make Connections - Plants and fungi sense changes in and facilitate the adaptation to their light environment. Light provides energy for photosynthesis and helps plants build carbohydrates. Fungi do not use photosynthesis for growth and development. The growth and development of your crops are influenced by genetics, fertigation, and grow room environmental factors like CO_2, temperature, humidity, and airflow in addition to light. Different properties of light interact to control yield and quality attributes of your crops. Learn about the interactive effects in cultivation spaces between your lighting, HVAC, and watering systems.

Balance Yield with Quality - Besides yield, quality affects the value of CEA products. Crops have to make choices when using light energy. If you provide a light treatment that encourages yield, crops may be more productive at the cost of quality, and vice versa. Crop quality factors are impacted by *photomorphogenesis* and expression of *phytochemicals*, biologically active compounds that serve a variety of helpful survival functions such as mechanisms for defense, reproduction, and differentiation. Light can induce *photomorphogenesis*, a physical effect on plants, and influence shape, appearance, color, flavors, aromas, and taste. Some *phytochemicals* like anthocyanin are desirable for their positive impact on nutritional content in food and aesthetic impact on floriculture crops.

Radiate Light - Light is *electromagnetic radiation*, a stream of massless particles *(photons)* traveling in a wave-like pattern, with each photon containing a certain amount of energy. Different types of radiation are defined by the amount of energy found in the photons. *Infrared* (IR) light waves have photons with low energies, with *visible light* having more energy, *ultraviolet* (UV) even more. Electromagnetic radiation is measured in terms of *wavelength* to describe spectral distribution of wavelengths from a light source[4].

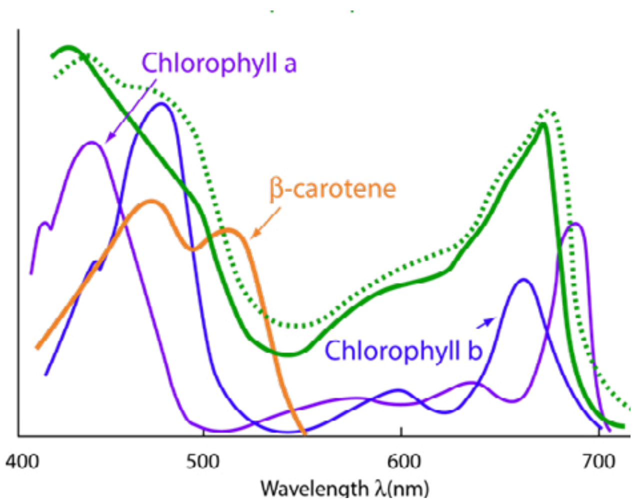
Lights On - The *photoperiod* experienced by your crop is the number of hours per day in which your plants or fungi are exposed to any kind of light source. *Short-day* crops like spring and fall-flowering plants need an uninterrupted period of darkness and flower only when the photoperiod is less than 12 hours. *Long-day* crops like lettuce bloom when they have photoperiods longer than 12 hours. Some crops like tomatoes, cucumbers, and some strawberries are *day-neutral* and form flowers regardless of day length.

Support Plant Photosynthesis - *Photosynthetically Active Radiation (PAR)* is the portion of the light spectrum that plants use for *photosynthesis*, the process by which plants convert light into chemical energy in order to harness and store energy for plant growth. PAR is not a unit but a range

[4] American Society of Agricultural and Biological Engineers (ASABE) ANSI/ASABE S640: Quantities and Units of Electromagnetic Radiation for Plants (Photosynthetic Organisms), 2017, and Illuminating Engineering Society (IES) ANSI/IES LS-1-20, Lighting Science: Nomenclature and Definitions for Illuminating Engineering, 2020. The DesignLights Consortium defines light fixtures or lamps as electromagnetic radiation-generating devices analogous to luminaires (or fixtures) or LED lamps (integrated and non-integrated) defined by ANSI/IES LS-1 sections 6.8.5 and 10.3.1 or 6.8.5.3 and 6.8.5.4, respectively.

of light energy that plants can use for their various growth cycles and biological processes. PAR wavelengths range between 400 nm (deep violet) and 700 nm (deep red). The impact of different wavelengths on photosynthetic processes[5] are shown in **Figure 1** below[6] and described in more detail in Table 3 on page 12. As technology develops and research continues, the CEA industry is still learning what light spectrum ranges do to influence crop development, yield, and quality expressions.

Figure 1: Photosynthetic Absorption Spectrum and Photochemical Efficiency



Provide Fungal Photopigments - Light regulates fungal development and behavior and activates metabolic pathways. Blue- and red-light *photoreceptors* sense light at either end of the spectrum of visible light and control very similar biological responses in both plants and fungi. Blue-light absorbing proteins and red-light sensing *phytochromes* optimize fungal spore dispersal and control the daily or seasonal timing of mushroom production.

Quantify Wavelengths - Humans and animals use the visible light spectrum to see; the light that we interpret and every color in the world falls somewhere within the bounds of 380 to 700 nm. **Figure 2** below shows an example of a *spectral quantum distribution* (SQD) graph which can help you visualize a light fixture's polychromatic spectrum made up of different quantities of photons. Note that **Figure 2** is normalized so that the wavelength with the maximum quantity of photons is shown as 100% on the Y-axis. SQD graphs describe the light spectrum that a light fixture provides, based on laboratory testing by the manufacturer. These visualizations tell you the percentage of light output by wavelength in units of µmol/s nm.

Figure 2: Spectral Quantum Distribution of LED Horticultural Light Fixture

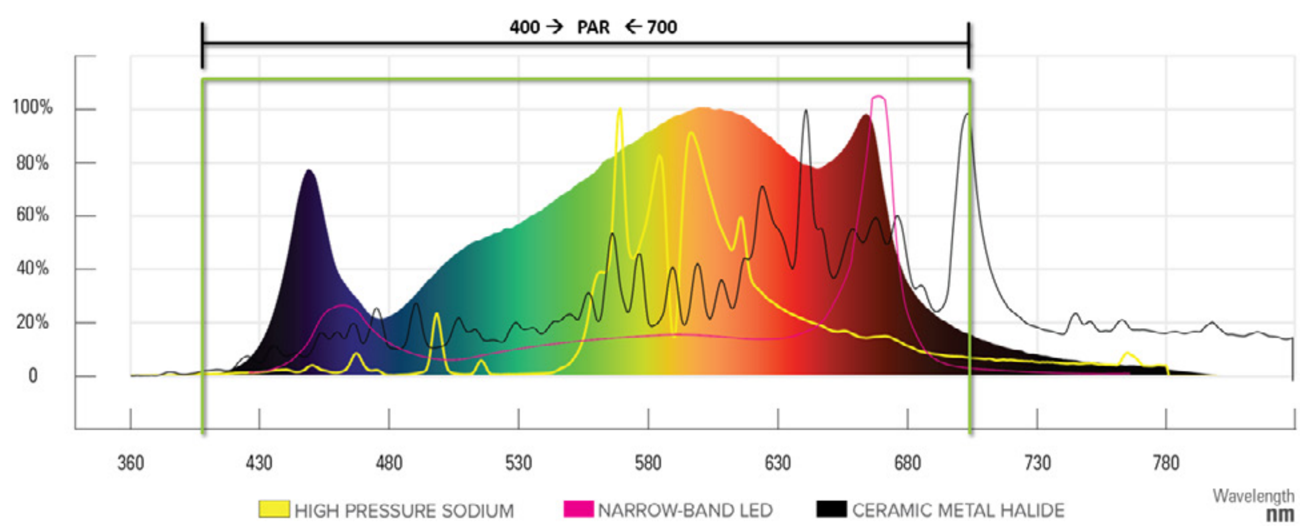


FIGURE 1: GEORGIA STATE UNIVERSITY; FIGURE 2: FLUENCE

[5] The McCree Curve Demystified, Tessa Pocock, 2018.

[6] Light Absorption for Photosynthesis, Georgia State University HyperPhysics, Department of Physics and Astronomy.

Be Blue - Blue wavelengths impact plant quality factors and can also result in deeper coloration (darker green and red leaves and flowers) and enhanced secondary metabolite expression but may decrease expression of other secondary metabolites. Using blue can result in more metabolites but lower yields, more compact plants, shorter stems, and smaller leaves. More blue light induces a stress response in all plants which can cause *stretch suppression*. Research on lettuce by Michigan State University has shown[7] that for lettuce, more blue light decreased fresh biomass by up to 63%. NASA experiments using LED spectral treatments at the lower blue end of the spectrum (UVA, UVB and near-UV blue spectra) observed much higher anthocyanin, improving nutritional content in food. Blue light can trigger the synthesis of nutritional secondary metabolites in some herbs, petite greens, and microgreens[8].

See Red - Red drives photosynthesis and yields and is a very important part of the spectrum for flowering plants like berries and floriculture crops. As wavelength gets higher, plants can create larger leaves, which can result in higher yields because bigger leaves are bigger collectors of photons; those extra collected photons can be used to generate more biomass, which results in more production of flowers and bigger fruits. This is not true for all crops as leaf expansion may be a result of a lack of blue photons. A lack of blue can induce a shade response, and that can result in a change in leaf area and leaf position. Note that red diodes are also the most energy efficient and LEDs with a high proportion of red can improve fixture efficacy.

Ratio Red:Blue - More blue light can also improve shelf life of leafy greens but greater blue photon proportion can increase bitterness; less blue light results in more delicate leaves with sweeter taste. Proportion of red to blue photons also impacts yield. Red:blue (R:B) ratio[9] can be tuned to maximize yield and minimize adverse quality impacts. A McGill University greenhouse tomato study[10] found highest biomass production (excluding fruit) occurred with a R:B ratio of 19:1. Lighting manufacturers may describe R:B using proportion of red. For example: an "R4" fixture might have 40% red diodes and an R8 fixture might have 80% red diodes.

Go Far - Far-red spectra are proving to be more useful light treatment than previously thought and act like a growth regulator. Phytochrome concentrations are affected by proportions of far-red light and trigger photomorphogenesis. This can be expressed as modified plant internodal spacing and leaf size. The Emerson effect describes the increase in the rate of photosynthesis after chloroplasts are exposed to light with wavelengths equal or greater than 680 nm (deep and far-red). Michigan State University studies have found more red or far-red photons can result in more delicate and less flavorful greens and note that some producers use far-red wavelengths during certain times of day to keep lettuce heads compact. Growers can use dedicated supplemental light fixtures to provide far red treatments.

Assess Extended Wavelengths - The extended PAR (ePAR) range has been documented in recent academic research[11] of 17 crop species to be 400-750 nm, which includes some far-red wavelengths. ePAR is not yet an industry-standard metric and cannot yet be measured and tested by laboratories based on testing requirements developed by ASABE like their standard S640. Some researchers argue that far-red photons should be included in the definition of photosynthetic photons, and that standards should be developed to quantify the amount of those photons being provided by horticultural lighting[12].

The impact of different wavelengths on photosynthetic processes are described in more detail in Table 3 on the next page.

7 Blue Radiation Interacts with Green Radiation to Influence Growth and Predominantly Controls Quality Attributes of Lettuce, Meng, Boldt, and Runkle, 2020.

8 Blue Wavelengths from LED Lighting Increase Nutritionally Important Metabolites in Specialty Crops, Kopsell, Sams, and Morrow, 2015.

9 Common R:B ratios used by designers use 450 nm for blue and 660 nm for red, but ASABE does not define blue or red as specific wavelengths. Stutte et al (2009) define violet as 400 - 450 nm, blue as 450 - 500 nm, and red as 610 nm - 700 nm.

10 Supplemental Lighting Orientation and Red-to-blue Ratio of Light-emitting Diodes for Greenhouse Tomato Production, McGill University, 2014.

11 Why Far-Red Photons Should Be Included in the Definition of Photosynthetic Photons and the Measurement of Horticultural Fixture Efficacy, Zhen, van Iersel, and Bugbee, 2021.

12 Got your lighting dialed in? Get ready for ePAR, Produce Grower, 2021.

Table 3: Summary of the Effects of Wavelength Ranges on Plant Growth[13]

Light	Wavelength[14] (nm)	Major Processes	Notes
UV-C	100 - 280	Secondary metabolism	Useful for protecting fruit and veg from spoiling after harvesting, pathogen control, and air and surface disinfection.
UV-B	280 - 315	Secondary metabolism, shade avoidance, phototropism	Useful for protecting fruit and veg from pathogens (powdery mildew) and from spoiling after harvesting. Affects (often increases) metabolites and defensive compounds; high levels disrupt growth.
UV-A[15]	315 - 400	Secondary metabolism, photomorphogenesis	
Blue	Approximately 400 - 500	Photosynthesis, shade avoidance, phototropism, secondary metabolism	Some level necessary for optimal photosynthesis (inhibit stem extension and plant height). 5-30% blue is typically desirable. Regulates stomata opening.
Green	Approximately 500 - 530	Photosynthesis, shade avoidance, secondary metabolism	Able to penetrate further through canopy than blue/red. Regulates plant architecture. Absorbed by photochemicals other than chlorophyll.
Yellow / Orange	Approximately 530 - 600	Photosynthesis, secondary metabolism	Using these wavelengths can increase growth and metabolites; results vary between species. Antagonistic to some blue light responses including phototropism, hypocotyl and flowering inhibition.
Red	Approximately 600 - 700	Photosynthesis, shade avoidance, photoperiodism, secondary metabolism	Highest action spectrum for photosynthesis; photosynthetically efficient. Consider ratio of red to far-red (R:FR).
Far-red	700 - 800	Photosynthesis, shade avoidance	Enhances photosynthesis; consider R:FR and phytochrome photostationary state, PSS. Increases extension growth (stem length, plant height, leaf size).
Infrared	800+	None / unknown	Not photobiologically active, heat radiation affects plants by affecting leaf temperature.

Balance Red:Far-Red - Consider red:far red ratio (R:FR)[16] to control compact growth and rapid flowering. Plants have different kinds of *photoreceptors* that absorb different wavelengths of light. Some of these photoreceptors are *phytochromes* which are particularly sensitive to the amount of red light relative to the amount of far-red (FR) light. Plants respond to the relatively high R:FR by increasing branching, producing more shoots, and thick, small leaves. A decrease in R:FR can induce *phototropism*, a shade avoidance response where plants adapt and grow to and elongate and position stems and leaves so they receive more desirable light conditions. R:FR also can influence flowering, especially in long-day plants. Research has shown that some plants flower earlier with moderate to low R:FR lighting systems.[17] Higher R:FR can delay flowering of some crops. Wavelengths used for calculating R:FR vary; for example 660 nm:730 nm may be used by one manufacturer or academic study but another may use different values.

13 IES Recommended Practice RP-45-21: Horticultural Lighting, 2021. University of Arizona Greenhouse Design Short Course, March 2022.
14 Wavelengths shorter than 350 nm typically blocked by glass greenhouse coverings; shorter than 390 nm typically blocked by polycarbonate coverings.
15 UVA can be either stimulating or inhibiting to crops depending on type and other environmental factors.
16 The R to FR Ratio, Runkle, 2011.
17 A Closer Look at Far-Red Radiation, Michigan State University, 2016.

Simulate Shade - Sunlight contains both red light and far red light, but daylight contains more red light than far red light. When phytochromes absorb red light, they change state, and change back once they absorb far red light. Phytochrome concentration[18] changes throughout the day and night due to the changing state of phytochromes. *Phytochrome photostationary state (PSS)* is a value between 0 and 1 that describes the ratio of red phytochromes to total (red and far-red) phytochrome concentrations[19]. Horticultural light fixtures use a PSS value to describe how products use far red light to simulate shade. For example, a "FR" light fixture could have a PSS value of 0.78 or 0.86.

Measure Photons - A *mole (mol)* is a way to describe a quantity of light; it gives us a way to describe light as amounts of photons. A photon is a packet of electromagnetic radiation and is the basic unit used to describe light. Because one mol is a very large number of photons, the unit of light often used in the horticulture industry is the *micromole (μmol)*. There are one million micromoles in a mole. Some lighting terms use micromoles (like Photosynthetic Photon Flux Density, PPFD) and some use mols (like Daily Light Integral, DLI).

Figure Out Flux - *Photosynthetic Photon Flux (PPF)* is the rate at which light fixtures produce light for photosynthesis. PPF is the total amount of light (number of photons measured in micromoles) within the PAR range produced per second measured in units of μmol/s. PPF is not the amount of light your plants will receive in your facility. PPF is the amount of light your light fixtures can produce; this does not mean it is the amount of light your fixtures will produce.

Maximize Efficacy - *Photosynthetic photon efficacy* defines a light fixture's ability to convert power from electric energy to achieve rated PPF when delivering light to your plants. The efficacy of light products is measured in units of micromoles per joule (μmol/J), and describes how much light a fixture produces from its input power. Many utilities and efficiency programs qualify products with PPE at or above 2.0 μmol/J for financial incentives.

Understand Intensity - *Photosynthetic Photon Flux Density (PPFD)*, is the quantity of photons within the PAR range, measured in micromoles, that hit a given area (a square meter) of your plant canopy per second. Crop canopy receiving PPFD of 250 micromoles per square meter per second of 730 nm light would have profound effects on plant biology, but have almost no intensity perceived by the human eye. For this reason *fluence rate* can describe the quantity of light your plants actually receive in your facility in a way that is not sensor-dependent. Light is needed during propagation for cuttings and seedlings to develop roots. Too much light can stress plants, bleach leaves, and reduce root formation. Higher light intensity increases biomass production and environmental factors like elevated CO_2 levels can allow crops to accept higher PPFD. Either light or CO_2 concentration can be the limiting factor for photosynthesis.

Figure 3: Effects of Light Treatments on Plants

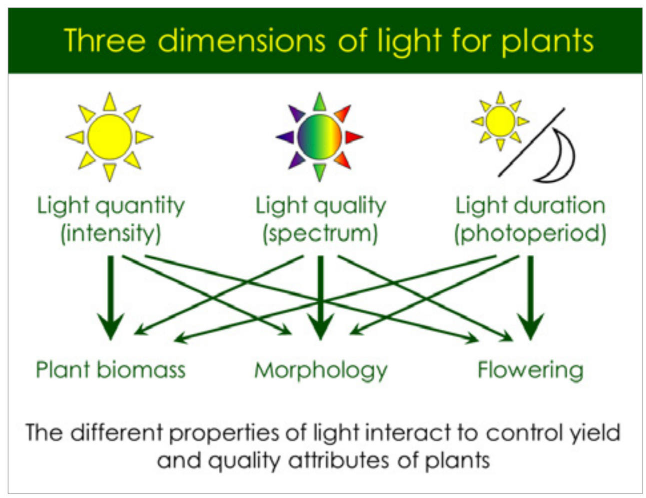


Figure 3 above demonstrates that both intensity and spectral treatment affect biomass production and quality characteristics. Academic researchers have shown that at lower DLI targets, spectral treatments can have more impact than PPFD, but at higher DLI, meeting target PPFD matters more than light recipe. Above DLI of 7 mol/(m2 day), PPFD matters more than spectral output. Note that photoperiod primarily influences flowering CEA crops but can also impact morphology and biomass production. Table 4 on next page describes key horticultural lighting terms and their units of measurement.

FIGURE 3 : DR. ERIK RUNKLE, MICHIGAN STATE UNIVERSITY

18 What is Phytochrome Photostationary State (PSS)?, UPRtek, 2022.
19 Sager et al. 1998.

Table 4: Terms for Visible Light and PAR Spectrum Light (Used by Plants for Photosynthesis)

Property	PAR Spectrum[20]
Light Fixture Output (photons)	PPF – Photosynthetic photon flux (μmol/s)
Light Fixture Efficacy (photons per input power)	PPE – Photosynthetic photon flux efficacy (μmol/J)
Light Intensity (photons per area)	PPFD – Photosynthetic photon flux density (μmol/(m2 s))
Light Delivered during Photoperiod (photons per day)	DLI - Daily Light Integral (mol/(m2 day)

Interpret Light Integral - *Daily Light Integral (DLI)* is the total accumulation of light across your crop canopy over single day periods from all light sources. Research has shown for full-sun food crops like leafy greens, vegetables, and berries that increasing DLI has a direct correlation to increases in biomass production[21]. Outdoor DLI accounts for light received by the Sun and accounts for daily and seasonal weather patterns, cloud cover, and change in daylight hours at your facility's location. DLI is very important for CEA greenhouses. *Mixed light facilities* use supplemental electric lighting to meet crop DLI targets when sunlight is not sufficient. Use **Figure 4** below to see how DLI changes throughout the year across various locations in the United States[22].

Figure 4: Maps of Monthly Outdoor DLI, United States

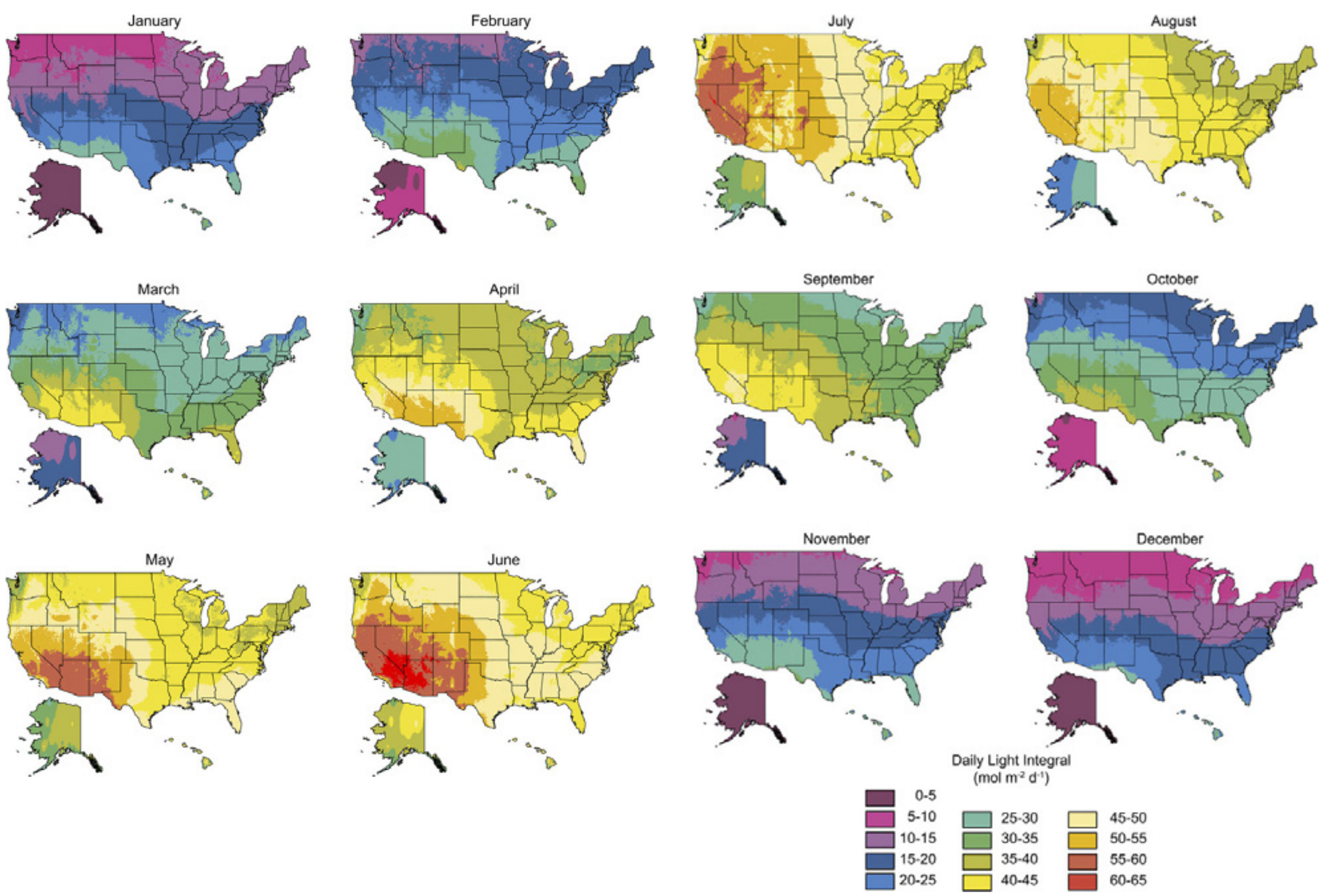


FIGURE 4 : DAILY LIGHT INTEGRAL: A RESEARCH REVIEW AND HIGH-RESOLUTION MAPS, FAUST, 2018" INSTEAD OF HORTSCIENCE

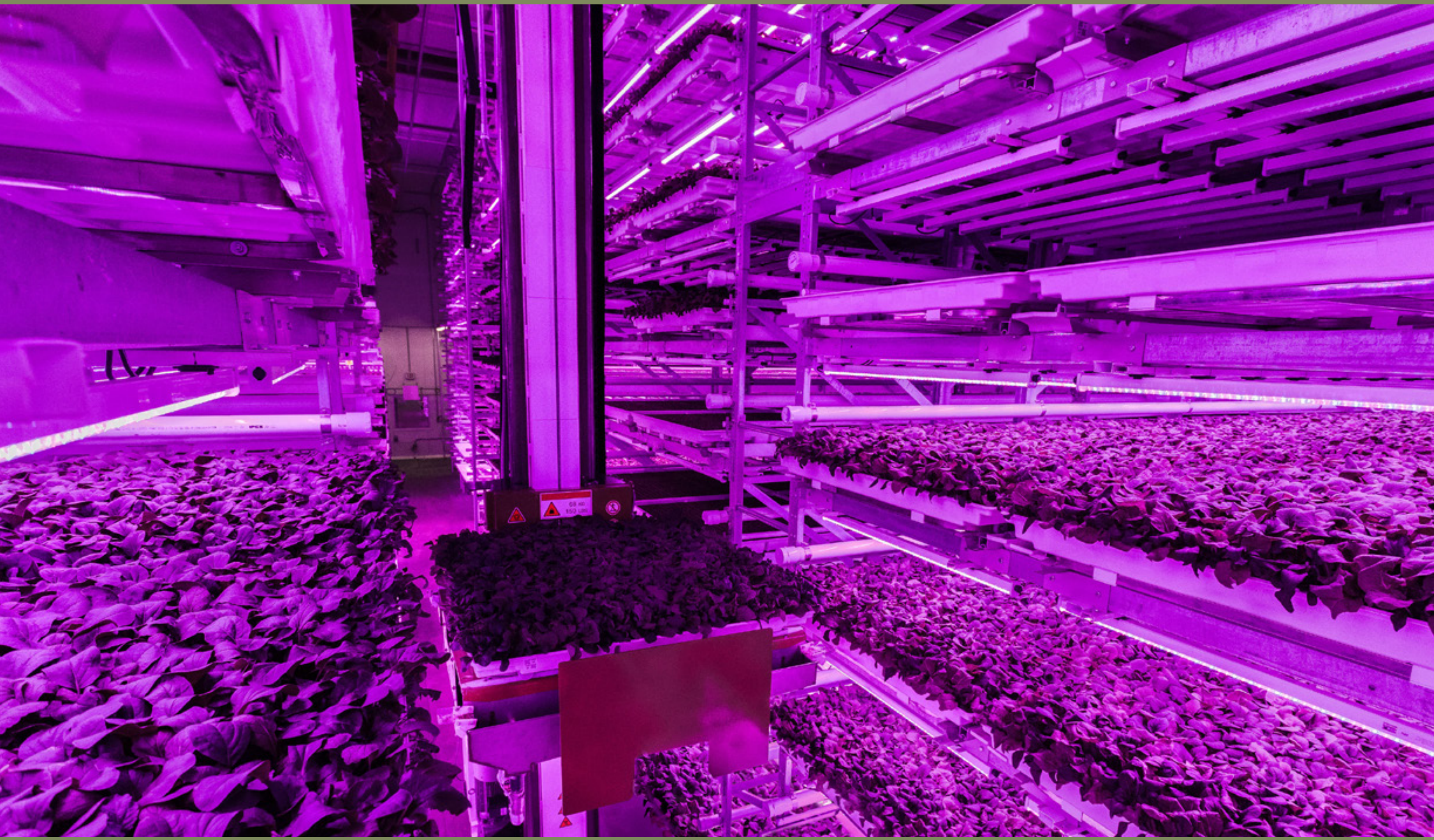
20 Quantities And Units Of Electromagnetic Radiation For Plants (Photosynthetic Organisms), ASABE, 2017.

21 Promotion of lettuce growth under an increasing daily light integral depends on the combination of the photosynthetic photon flux density and photoperiod, Kelly, Choe, Meng, and Runkle, 2020.

22 Daily Light Integral: A Research Review and High-Resolution Maps of the United States, Faust, and Logan, HortScience, 2018. An interactive version of these maps are available at https://webgis.coe.clemson.edu/storymaps/light-integral-map/.

SECTION

02



Understand CEA Lighting Options

PHOTO: FIFTH SEASON

Crop and facility type impact the lighting solutions you may need to achieve your goals for production and efficiency. Learn how CEA crops benefit from diverse light treatments. Greenhouses and indoor farms can maximize different benefits of LED lighting.

Major drivers of CEA facility profitability are labor and energy costs, crop yields, and product quality. Capital expenditures for many cultivation operations are in the six to seven figures, and with energy representing 30 to 60% of the operational expense of indoor and greenhouse facilities producing a range of crops, this variability in energy efficiency represents profit potential. Increased demand for products and cost compression in CEA markets have led to new attitudes about efficient and optimized HVAC systems, as growers consider energy and resource efficiency to rise above the competition by reducing operating and maintenance costs through using high-performance systems.

When assessing lighting options, CEA producers growing plants and mushrooms have different goals that are influenced by facility type. Growing some crops in greenhouses may be possible without supplemental lighting, whereas crops in indoor farms must receive all of their light input from sole source lighting solutions.

Return on investment for CEA lighting systems is multifaceted and depends on crop type, facility type, geographic location, support from utility efficiency programs, and facility energy costs. Some CEA crops have higher retail value than others, and producers may have a bigger appetite for longer returns on investment (payback periods). Greenhouse growers may be interested in extending seasonal production windows and boosting yields per harvest on lower-margin crops. Some operators may be able to get generous financial incentives for high-performance lighting equipment, while others may be located in a region without efficiency program support for CEA producers. Even without the support of efficiency programs, it can still be beneficial for CEA growers to use efficient lighting equipment.

Many diverse products are created in controlled environments. At the start of this journey, CEA producers and project teams should understand common CEA crops and the typical facilities used for production. Some crops may have sprouts of seedlings grown indoors before being moved to greenhouses for later growth stages.

Key: Greenhouse ● Indoor ●

Vine Crops

Cucumbers and indeterminate tomato varieties are mostly grown vertically on high wires in greenhouses. Depending on facility location, some facilities may need supplemental lighting solutions to meet DLI targets.

Vegetables and Herbs

Vegetables like peppers and herbs like basil are grown in greenhouses and indoor vertical farms. Leafy greens are grown by both greenhouses and indoor facilities. Dwarf determinate tomato varieties are grown in greenhouses and are starting to be cultivated indoors. Facilities growing vegetables and herbs may need supplemental or sole-source lighting depending on facility type and environmental targets for crop production. Microgreens are generally grown only by indoor farms and must use sole-source lighting solutions.

Floriculture

Nursery crops (young plants), cut flowers, and finished crops (bedding plants) are often cultivated in greenhouses or outdoors. Ornamental crops may or may not need supplemental lighting depending on facility location and crop quality goals. Some do not use supplemental lighting except for nursery crop propagation stages of plant growth. Other producers like those growing cut flowers and potted plants may use more supplemental lighting for certain cultivars. Producers may use supplemental lighting for improvements in the finishing stage of growth by changing DLI and adjusting photoperiod to induce or inhibit flowering for potted crops. Lighting system usage is increasing more as LED technology advances to speed up production, improve plant quality, and manage pathogens.

Mushrooms

Mushrooms are primarily commercially cultivated indoors. Some greenhouses cultivate mushrooms under benches and grow vegetables or other crops above them. Changes in environmental factors can signal fungi to *initiate reproductive processes and build fruiting bodies. Light can trigger pinhead formation for some mushrooms. Some mushrooms need a phase of darkness and a phase with light to start pinhead formation. These types of mushrooms have genes that are responsible for the circadian clock that respond to blue light, and other genes that act like red light and far-red light phytochromes.*

Berries

Strawberries and other berries have historically been grown in greenhouses but are starting to be cultivated indoors. Depending on light intensity targets and facility type, electric lighting solutions may be necessary for optimal fruit production.

What Sells - Final products grown by facilities dictate the diverse production processes that impact CEA lighting energy consumption. Understand the stages of growth and associated activities performed at your facilities to determine which lighting systems and strategies will be best suited for the application. **Figure 5** below illustrates the stages of plant growth for CEA crops.

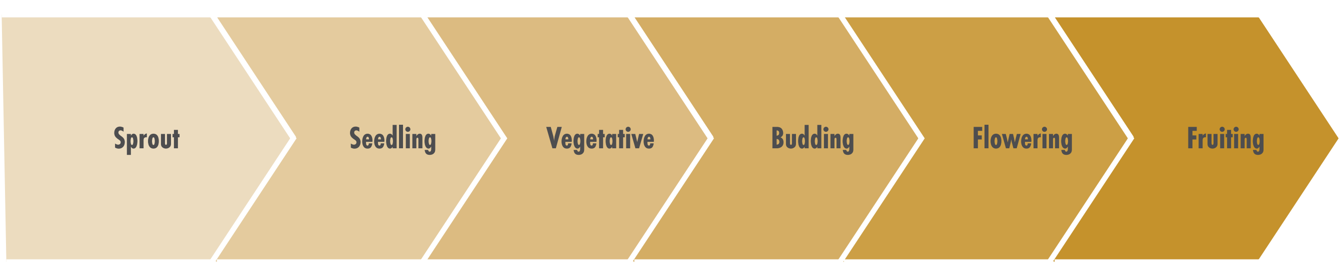
Determine Lighting Needs - Lighting demands mostly depend on cultivation approach and target light intensity for crops. **Table 5** at right describes the intensity of horticultural lighting applications for popular CEA crops based on their required *daily light integral* (DLI)[23]. When grown in greenhouses, the need for supplemental lighting may be lower than for indoor facilities, and will also vary depending on facility location.

Table 5: Intensity of Horticultural Lighting Applications by Crop Type

Crop Type	DLI Target[24] (mol/(m2 day)	Horticultural Lighting Application
Cucumbers	15 - 30	Medium-High
Tomatoes	20 - 30	High
Peppers	20 - 30	High
Greens	12 - 17	Medium
Herbs & Microgreens	12	Low-Medium
Strawberries	17 - 20	Medium
Mushrooms	2 - 3	Low
Floriculture	2 - 30	Low-High

Consider Facility Type - For greenhouses located in a region with lower solar resource, supplemental lighting solutions may be used for more days of the year, or at higher intensities, to meet the DLI targets for your crops. For crops grown indoors, like vegetables, herbs, and mushrooms, you are in complete control of both the photoperiod and the light intensity of your facility's sole source lighting solutions. For example, to meet a target DLI of 16 mol/(m^2 day), a lighting system serving tiers of a vertical lettuce rack could be operated at 270 μmol/(m^2 s) for 16 hours a day, or could also be operated at a lower light intensity (like 180 μmol/(m^2 s)) for a longer photoperiod (like 24 hours) to achieve the same DLI. Balance yield and quality by understanding the peak light intensity at which your CEA crops perform best. Some crops like strawberries do not grow well at PPFD higher than 350 μmol/(m^2 s) and may require elevated CO_2 levels at PPFD levels greater than 220 μmol/(m^2 s).

Figure 5: Growth Stages for Cultivation of CEA Crops



[23] The total accumulation of light across a crop canopy over single day periods from all light sources.

[24] Data from Daily Light Integral: Are your plants receiving the right amount of light?, citing research done by Dr. Neil Mattson, Director of Cornell University Controlled Environment Agriculture group; Mushrooms on Mars: A Subsystem for Human Life Support, 2019 International Conference on Environmental Systems; IES Recommended Practice RP-45-21: Horticultural Lighting, 2021.

Pick the Right Light - Along with facility type and crop type, the stages of plant growth that occur in your cultivation spaces can also influence the lighting equipment you choose. There are various kinds of horticultural lighting systems used by CEA producers depending on the crop and light levels required by stage of plant growth. High-performance horticultural lighting products fall into two major categories: narrow band and full spectrum. *Narrow band* LEDs provide photons in a selection of wavelengths (typically blue and red) and often have a higher proportion of red diodes, increasing fixture PPE. *Full spectrum* LED fixtures produce polychromatic white light composed of photons from a range of wavelengths and often have a higher proportion of white or blue diodes, reducing fixture PPE.

Review Performance - Table 6 below describes the traditional and high-performance light fixture options available for the three major phases of CEA crop production. Of the 560 tested[25] products listed on the DesignLights Consortium Horticultural Qualified Products Library as of February 2022, 95% of listed products have a *luminaire* PPE of 2.95 µmol/J or lower. LED fixtures with PPE >3.0 are available, though you may find that 3.6 - 3.8 umol/J may be the highest PPE that works for your return on investment as fixtures with PPE above 4 are more expensive. Note that LEDs with higher photon efficacies (PPE) require certain spectral combinations (narrow band fixtures with high proportion of red diodes) and operating conditions (dimmed to 50%). Fixtures with very high PPE typically have little or no green photons, and have low color rendering index values which both make it more difficult for humans to see.

Table 6: Typical Lighting Equipment for Stages of CEA Plant Growth

Category	Characteristic	Sprout / Seedling[26]	Vegetative / Budding	Flowering / Fruiting
Traditional	Fixture Type	T5 HO T8 T12	HPS	HPS
	Wattage Range	60 - 435 W	400 - 1,000 W	650 - 1,000 W
	Luminaire PPE Range[27]	0.7 - 1.2 µmol/J	1.0 - 1.7 µmol/J	1.0 - 1.7 µmol/J
High-Performance	Fixture Type[28]	LED	LED	LED
	Wattage Range[29]	15 - 200 W	150 - 600 W	150 - 1,200 W
	Luminaire PPE Range[30]	1.8 - 3.0 µmol/J	1.8 - 3.0 µmol/J	1.8 - 3.0 µmol/J

Table 7 on the following page shows how PPE varies depending on the wavelength of light produced by an LED *luminaire*. Note that note all of these wavelengths can be produced by commercial products. LED horticultural lighting equipment available today generally uses boards of white, blue, and red diodes to create customized spectral treatments. LED manufacturers make 660nm red pretty much exclusively for horticultural applications to match the major photosynthesis absorption peak. Refer to the photon efficacy values for blue, red, and full-spectrum wavelengths in the table to understand how spectral treatments with different proportions of white, red, and blue diodes may affect fixture efficacy. Observe how more red can increase PPE above 3.0 µmol/J.

25 DLC listed products are tested at OSHA/NVLAP accredited testing laboratories.
26 Note that fixture wattage can be at the low end of the range for the seedling stage, and even lower in tissue culture.
27 This range reports fixture efficacy. For light fixtures that use bulbs, note that light loss factors from bulbs reduce total lighting system efficacy further.
28 The type of LED fixture can influence wattage; linear LED fixtures can be at the low end of the range.
29 Mounting height can influence preferred fixture characteristics; vertical indoor farms may use lower-wattage LEDs when growing in narrow tiers.
30 Academic researchers have validated photon efficacy of LED luminaire packages in studies such as Photon efficacy in horticulture: turning LED packages into LED luminaires; results from this study are reproduced in Table 6.

Table 7: Typical LED Luminaire Package Photon Efficacy by Various Wavelengths

Peak Wavelength[31]	Photon Efficacy[30]
450 nm	2.8 µmol/J
470 nm	2.4 µmol/J
500 nm	2.0 µmol/J
530 nm	1.3 µmol/J
590 nm	1.1 µmol/J
620 nm	3.4 µmol/J
635 nm	2.5 µmol/J
660 nm	4.1 µmol/J
730 nm	3.6 µmol/J
850 nm	3.0 µmol/J
3000 K (full spectrum)	2.8 µmol/J
6500 K (full spectrum)	2.9 µmol/J

Utilities and efficiency programs support the adoption of emerging technologies like LED horticultural lighting based on the energy savings over traditional options. Throughout this guide, opportunities for efficiency program support of efficient lighting equipment will be highlighted with **bold green** text so you can work with your local program teams to get technical assistance and financial incentives for installing high-performance lighting solutions.

Optimize Lighting Designs for CEA Facilities

Determine the goals of your lighting systems by using your horticultural lighting vocabulary to establish design conditions for CEA lighting systems. The crops you grow, your facility type, and location inform your choice of lighting equipment, spectral treatment, and fixture layout.

Document Goals - Consider the basis of your facility design so that you can optimize the efficiency and impact of your lighting decisions. A *basis of design* gives designers and installers a better understanding of the details of your operation, and allows them to specify and construct lighting systems that meet your expectations. For indoor operations, it is most important to determine desired light levels you would like to maintain, and for greenhouse operations, to establish prefered DLI targets for your crops.

Prepare Your Facility - Supply your operation with 480V 3-phase electrical power if possible, especially if building a new CEA facility. This can reduce the infrastructure costs for powering lighting systems by lessening the amount of copper needed for wiring. Typical horticultural lighting systems are served by AC power at 277V. There are more products available that run at higher voltage. There are also energy savings benefits of running at higher voltage as fixtures operate with higher efficacy. If building a new CEA facility, consider all horticulture lighting technologies, from traditional to liquid cooled to centralized DC power, to determine the best fit to maximize efficiencies for the project.

Separate Power Supply- LEDs using integrated centralized remote power server systems move the power

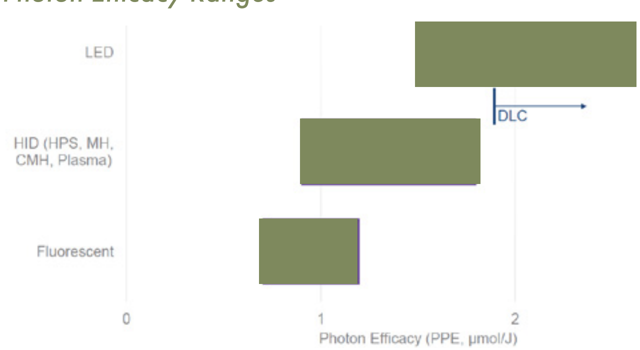
[31] American Society of Agricultural and Biological Engineers (ASABE) ANSI/ASABE S640: Quantities and Units of Electromagnetic Radiation for Plants (Photosynthetic Organisms), 2017.

supply out of the cultivation space, which can reduce the weight of fixtures, a benefit to greenhouse producers. Indoor operations can use remote power technology to eliminate ballasts as a source of heat affecting HVAC loads in grow rooms.

Direct Light - Consider how light might be provided to crops. Will top lighting be used alone? Will intracanopy lighting systems be employed? Set DLI targets for cultivation spaces and understand how much light different systems might provide. Some Lighting Working Group members find that for high wire crops, 20 - 30% of lighting budget may be spent on intracanopy lighting. Growers may choose to install a single line or double lines of intracanopy lighting depending on the height of the crop canopy.

Plan for Automation - Determine the ways horticultural lighting equipment could be controlled in your facility and whether controls hardware and software may be used to automate operation. Document monthly or weekly schedules for lighting operation based on the maximum usable light intensity of crops, and target DLI for your plants by stage of growth. For greenhouses, consider how lighting equipment will respond depending on available solar resource. Dimming strategies can be beneficial for all CEA facilities as a way to tailor light treatments as plants grow taller, smooth spikes in HVAC system operation, and save energy.

Figure 6: Horticultural Light Fixture Photosynthetic Photon Efficacy Ranges



Gather Information - Determine the area of the cultivation spaces in your facility that will need sole-source or supplemental lighting solutions. Determine goals for lighting system efficiency by sharing your range for acceptable PPE with your project team members. Figure 6 at left illustrates how PPE targets will inform selection of fixture type.

Choose Light Recipe - Spectra impacts PPE and some light recipes are more energy-efficient and can save money in operation. LEDs are the only type of grow light that has customizable spectral quantum distribution; manufacturers can provide unique light recipes targeting specific plant responses. Compare PPE of several light fixtures with various R:B ratios and PSS values to understand the impact on fixture PPE. Remember that far-red light does not count towards PPE calculations.

Estimate Field PPE - While PPE is an important metric to rate overall efficiency of lighting equipment and estimate how it may operate in your facility, PPE does not reflect actual product efficiency that your equipment may experience in the field. PPE changes depending on spectral output and input power. As LED light fixtures have more proportion of red, PPE increases. As fixtures are dimmed, PPE can also increase, saving energy. Consider how the light recipes of the fixtures you are evaluating affect average cultivation space PPE. Quantify fixture PPE at expected operational power and spectral treatment and average them across all fixtures in grow rooms.

Consider Spectral Tuning - You may want to choose several spectral treatments for different phases of growth or various crop types in your facility to maximize yields or quality characteristics. Some light fixtures can provide multiple or completely customizable spectral distributions so growers can adjust the spectrum dynamically as desired to tailor lighting on a granular level. This technology is still developing so there may be less products to choose from. Inquire with manufacturers about the crop-specific research they can provide to demonstrate the influence of the spectral treatments their fixtures can provide. Growers using spectrally tuned lighting systems will need spectroradiometers to verify spectral output; this equipment can be prohibitively expensive for some growers.

Calculate Mounting Height - Mounting height affects light levels received at the canopy level. LED solutions are advantageous in vertical indoor facilities because they

FIGURE 6 : ERS

emit less heat and fixtures can be mounted very close to the plant. Racked vertical growing arrangements are more feasible with LED fixtures mounted within 12 inches of crop canopy. Supplemental light fixtures in greenhouses are typically mounted high above the canopy, near gutter height, anywhere from 3 to 10 feet above the canopy. Ask members of your design team and lighting product manufacturers for suggested mounting hiehg based on growing approach and crop.

Maintain Uniformity - Understand the layout of cultivation spaces and location of walkways which impact spacing of fixtures, *uniformity*, and spill light impacts. Uniform light levels are necessary for your crops to receive consistent light intensity. Fixture spacing and mounting height contribute greatly to uniformity. Continuous runs of linear LED fixtures can improve uniformity compared to grids of traditional HID fixtures. Ensure consistent spacing in both X and Y directions in your cultivation space. Consider how light fixture placement and layouts impact light levels on edges of benches.

Choose Fixture Shape - *Form factor* is used to describe the shape of a light fixture and the selection of form factor is influenced by facility type. Form factor can affect ease of installation and operation of lighting systems in your facility. Because of the layout and arrangements of cultivation environments, the shape of a light fixture can impact how you hang it, how you set it up, and how you run it to accommodate the unique aspects of your grow room or greenhouse. In greenhouses, it is important to minimize light fixtures shading your crop. Larger fixtures mounted close to the plant canopy may block daylight; thoughtful combination of form factor and mounting height can minimize shadow footprint. For indoor operations, the purpose of the lighting system can impact form factor choice; intracanopy light fixtures are often linear so they can be easily mounted in racks.

Understand Interactive Effects - Consider the interactive effects of lighting and HVAC systems and retrofit to LED light fixtures thoughtfully. If your grow spaces were originally designed for HID lights, retrofitting spaces to LED will change the heat loads of the space as LED lights emit less radiant heat (often expressed as Btu per hour, or Btuh) as illustrated in Figure 7 below. The system on the left demonstrates an LED luminaire and on the right an HID luminaire. To keep greenhouses at the same temperature, more HVAC capacity for heating may be required in colder climates. Consider increasing lighting density when retrofitting to LED to offset the reduction in radiant heat from LED fixtures so your CEA facility doesn't need to substantially change HVAC systems or add heating capacity.

Figure 7: LED and HID Lighting Systems Light and Heat Efficiency

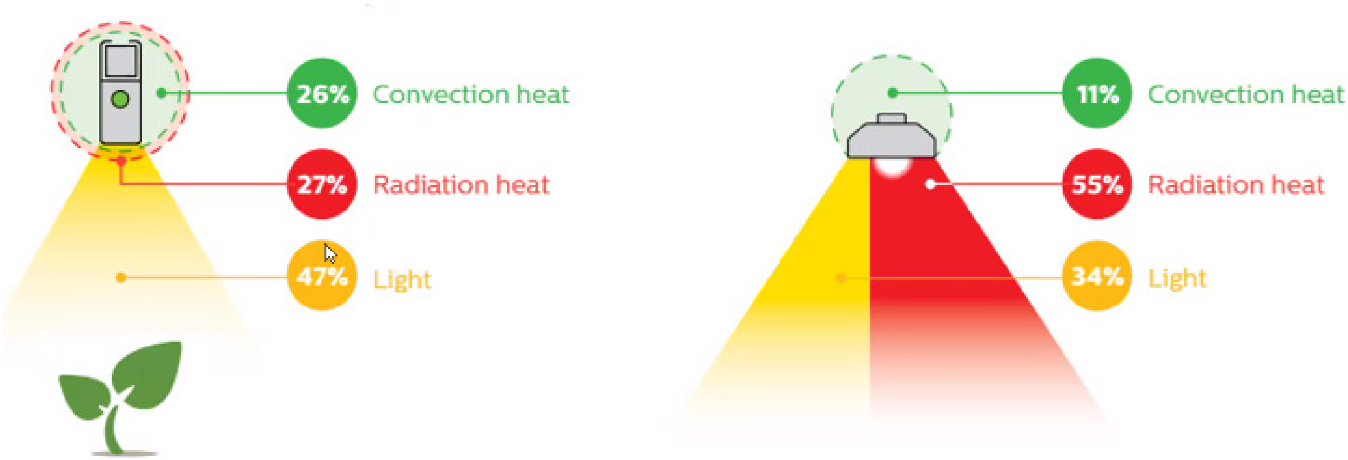


FIGURE 7: "FUNDAMENTALS OF SUPPLEMENTAL AND SOLE SOURCE LIGHTING FOR CEA" BY ROBERTO G. LOPEZ AND ERIK S. RUNKLE
DEPARTMENT OF HORTICULTURE MICHIGAN STATE UNIVERSITY

Understand Ballasts - *Ballasts* supply power to HID lighting systems, *drivers* supply power to LED systems. A significant portion of the heat associated with HID lights are generated by ballasts. LED drivers are 92 - 95% efficient, so the power supply of a 630W fixture may emit 40W of heat, which equals 140 Btu per hour (Btuh). Most LED light fixtures have internal or external drivers which produce some heat and may require separate mounting features. Ballasts and drivers may also contribute to shading in greenhouses. Ballasts and drivers are failure points, and when they need replacement, they can require accessing and removing the entire light fixture. Some CEA greenhouses and indoor vertical farming operations may appreciate the heat emitted by lighting systems and use it to offset HVAC capacity for heating.

Pick PPFD - Understand the ranges of PPFD necessary for your plants' growth, like minimum and maximum PPFD. PPFD targets describe the light levels for supplemental or sole source lighting systems to maintain at the plant canopy. In greenhouses, the PPFD target may be met by sunlight during some hours of the year. For indoor vertical farms, the quantity of light fixtures to maintain PPFD for crops depends on the number of racking levels for cultivation. Refer to the ranges offered in Table 8 right to inform your light intensity targets for greenhouses and indoor farms and number of tiers for vertically racked indoor facilities.

Table 8: Light Intensity Targets and Vertical Racking Levels for CEA Crops

CEA Crop	Target PPFD Range	Vertical Racking Levels
High Wire Vine Crops	450 - 600 (toplight) 120 - 250 (intracanopy)	1 layer of toplighting + 1-2 layers of intracanopy lighting
Vegetables	350 - 600	2 - 3+
Leafy Greens	180 - 270	4 - 6+
Microgreens & Herbs	130 - 250	4 - 6+
Floriculture	40 - 600	1
Mushrooms	0 - 100	4 - 8+
Berries	220 - 350	1 - 2+

Learn from Manufacturer Models - Work with your project team to calculate the quantity of light fixtures needed to achieve design targets. Many manufacturers of horticultural lighting offer free design assistance using lighting design software programs[32]. Lighting plans from manufacturers provide a lot more value than a specification document; their guidance can influence the ultimate mounting height and spacing of your light fixtures. You may have to decide what is more important: higher uniformity, which can require more fixtures, or lower uniformity which can save you capital and operating dollars, as long as the canopy is getting what it needs. Manufacturer plans offer estimated PPFD targets and uniformity, and can specify layouts so you can achieve your target PPFD. See Figure 8, on the next page for an example of the kind of details manufacturer models can provide.

PHOTO: PETR MAGERA

[32] Lighting manufacturers use IES files to describe how light from a luminaire is distributed in a room. It is standard practice in commercial building design for these files to be provided by manufacturers so that lighting designers can simulate how a project will look when a specific light source is used. Unfortunately, horticultural lighting models are often only provided by a lighting manufacturer, as IES files for horticultural lighting are not commonly shared between manufacturers and lighting designers. Interested parties need to ask manufacturers directly for .ies files representing the luminaire's distribution (not sufficient to get just the lamp distribution).

Figure 8: Example Manufacturer Lighting System Layout and PPFD Map

"Room Name"

Slots (Lights) per Section	7	
Sections (Bars) per Room	6	
Light Spacing	5.0	ft
Section Spacing	4.2	ft
Height	6	ft
Room Y (section length)	35	
Room X (sections*section sp)	25	ft
Light Type	Zenith DD	
Count	42	Lights
Light PPF	3133	PPF
Light Power	1200	W
Total Light kW	50.4	kW
Total PPF	131586	PPF
Total sqft	875	sqft
Power Density	57.6	W/sqft
Crop Area DLI	69.9	mol
Average Room PPFD	1618	umol/m2/s
Median Plant Area PPFD	1639	umol/m2/s

Light sections are ALWAYS vertical columns in this sim.

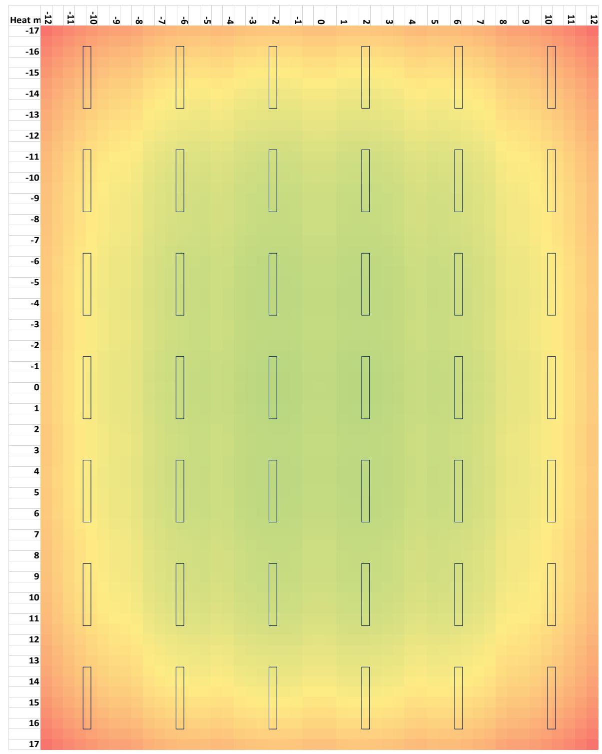
0	Top Bdr
0	Bot Bdr
0	L Bdr
0	R Bdr

Crop Area Average
1618 umol/m2/s

	# Cells	In %	Out sqft
Cells in plant area	3381		
within 10% intensity	3377	100%	-1
within 5% intensity	3177	94%	-51

	PPFD Legend Key min	center	max	PPFD
In Plant Area	1472		1691	+/- 109
10% Limits	1475	1639	1802	+/- 164
5% Limits	1557		1721	+/- 82

Heatmap & Stats



This heatmap calculation assumes 85% reflective walls, and a 0% reflective floor/plant surface. All estimates are from nominal output at 100% power. This is a good estimate room performance with large plants present.

FIGURE 8 :AGNETIX.

Review PPFD Maps -Fixture arrangement, fixture type, and mounting height of your fixture (which affects the distance from the light fixture to the plants) all impact PPFD measured in the field. Ask manufacturers to offer more than just peak PPFD and provide *point-by-point* light level values at consistent spacing. Work with your lighting designer to decide lighting configurations that work for your specific crop and priorities. Lighting Working Group members suggest using a spacing of no more than 12" apart for fixtures installed less than 3 feet from canopy level and up to 24" apart for fixtures mounted higher, the needs of each individual facility will differ. Some manufacturers model PPFD on 6" grids. For greenhouses, tighter spacing may be beneficial when modeling the variability of available sunlight throughout the year. Ensure elevation measurements are modeled at the intended finished canopy height and also the media height for most shorter crops like lettuce.

Account for Transmission - Understanding DLI from sunlight is critical to establishing an effective supplemental lighting strategy for greenhouse operations. Account for light transmission of greenhouse coverings. Glazing materials with lower *light transmission* can increase greenhouse supplemental lighting needs. Some greenhouses with specialized coatings allow sunlight to achieve target light levels for crops during parts of the year without using any supplemental lighting. Review product specification sheets and consider how light transmission light transmission might be reduced over time as coverings age. Light transmission can reduce by 30 - 50% over time for poly and glass coverings.

Estimate Natural DLI - Understand the average DLI during the lowest-light period of the year at your location. To quantify how much sunlight a greenhouse canopy receives throughout the year, reduce solar DLI for each month by the light transmission percentage. For example, if a facility receives 30 moles per square meter of sunlight per day in March, but a covering has a visible light transmittance of 66%, only 20 mols per square meter make it into the greenhouse that month. If this example flowering cannabis greenhouse has a DLI target of 35 mols per square meter per day, 16 mols/m^2 must be provided with supplemental lighting systems. In addition to the light loss caused by greenhouse glazing, overhead structural components can further reduce the amount of light that reaches to crop canopy. A reasonable rule of thumb is to assume 50% overall light loss in a greenhouse (averaged over a typical year).

Calculate Lighting System DLI - Determine crop needs based on cultivar and stage of growth. To choose a target DLI, determine the maximum PPFD inside your greenhouse and use that as a setpoint in μmol/m²/sec and convert using the formula below (see example of 250 PPFD converted to 14.4 mols/m²/day). DLI setpoints for lighting controls systems should be set at the target DLI value in seasons where DLIs from the sun are below target values. Conversely, DLI setpoints should be set slightly below DLI target values in seasons where DLI from the sun is expected to exceed target values, unless shading systems are used and integrated for measurement-based response to prevent exceeding target DLI.

Figure 9: Formula for Converting PPFD to DLI

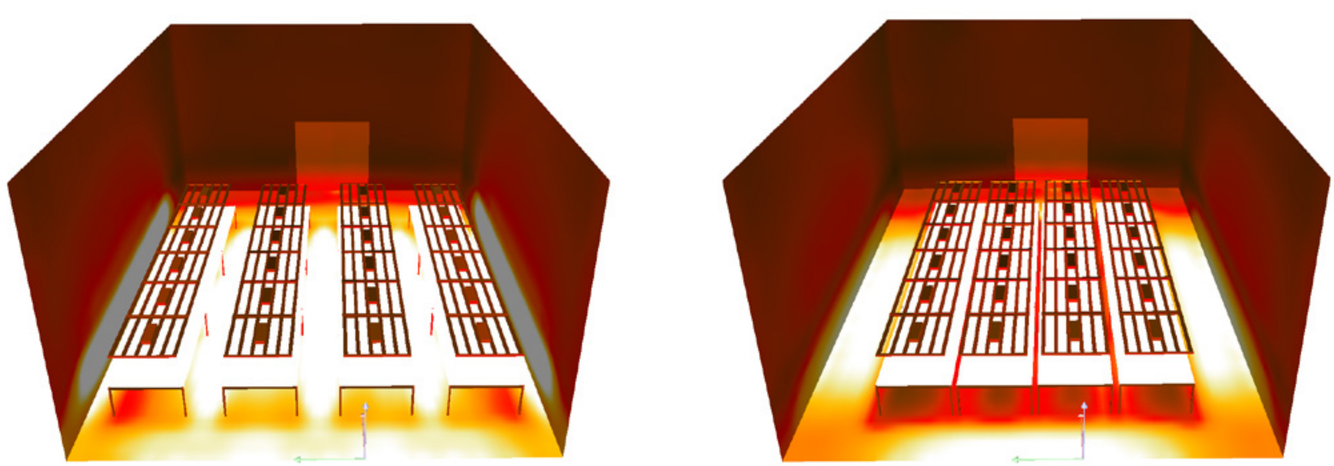
$$DLI = \frac{PPFD\left(\frac{\mu mols}{m^2 s}\right) \times 3600\left(\frac{s}{hour}\right) \times Photoperiod\,(hours)}{1{,}000{,}000\left(\frac{\mu mol}{mol}\right)}$$

$$DLI = \frac{250\left(\frac{\mu mols}{m^2 s}\right) \times 3600\left(\frac{s}{hour}\right) \times 16\,(hours)}{1{,}000{,}000\left(\frac{\mu mol}{mol}\right)}$$

DLI = 14.4 mol/m²/day

Minimize Spill Light on Your Walkways - *Spill light* is used to refer to the light delivered by fixtures used for growing that ends up on walls and walkways instead of being received by your plants. Efficient space utilization combines an understanding of spill light with a strategy to minimize walkway area. Figure 10 below shows a cultivation space with rolling benches. The graphic on the left shows a baseline layout, and the graphic on the right shows an optimized walkway layout for a cultivation space. The space on the right maximizes the light energy received by plants by ensuring that light spilled from one bench hits the growing area on the next bench rather than walkways. When reviewing manufacturer or lighting designer models, review light levels at all areas of benches, including edges. Minimize spill light and maximize PPFD by using reflective and light-colored walls, ceilings, and floors. Bright finishes optimize cultivation spaces for both biomass yields and energy efficiency.

Figure 10: Impacts of Spill Light in Cultivation Spaces



Purchase Lighting Equipment for CEA Facilities

Now that you understand the vocabulary used to describe the light your plants need and the metrics of performance for LED lighting, you will need to apply them to make informed decisions when selecting fixtures for your facility.

Gauge Your Appetite - The purpose of the installation or retrofit influences the target return on investment for lighting projects. Lighting installs can focus on improving crop yields, shaping crop quality, saving energy, and serving new or expanded canopy area. High-performance lighting projects may be more feasible for certain types of facilities. For instance, greenhouses may experience longer payback periods for LED lighting than indoor farms due to lower hours of use and typically lower light intensities.

Consider Your Options - Depending on your facility type, crops, and business goals, different light fixtures may be more appropriate for your operation. Greenhouses consider crop shading and often elect to use linear fixtures or high-bay fixtures with slim profiles or intracanopy lighting solutions. Vertical indoor operations may use linear fixtures in racks or intracanopy installations and vertical installations growing high-wire crops may use high bay fixtures for toplighting of crops needing higher PPFD. If a facility is retrofitting from HID to LED fixtures, a new form factor may be possible and beneficial for CEA crops.

Anticipate Regulations and Standards - Be aware of regulations that could affect your CEA operation. The state of California has adopted updates to Title 24, Part 6 related to CEA, the first regulations specific to horticultural lighting for the state, which will take effect in January 2023. The code will be triggered by new construction and major renovations and applies to greenhouses and indoor farms with more than 40 kW of total connected horticultural lighting load. The proposal requires a minimum PPE of 1.9 μmol/J for luminaires used for indoor facilities and a minimum PPE of 1.7 μmol/J for luminaires used in greenhouses. Standards organizations are similarly establishing values for minimum efficacy. ASHRAE has mirrored this proposal and has drafted additions to

the 90.1-2019 Energy Standard for Buildings which would require luminaires in greenhouses and indoor farms to meet the same minimum PPE requirements.

Review Manufacturer Literature - Manufacturers' specification documents, often known as *specification sheets* or *submittals*, describe the performance characteristics of equipment so you can determine if it will meet your needs. These documents are where you will find the performance metrics covered earlier in this guide. Compare lighting technology using metrics like PPF, PPE, and input wattage to understand what type and wattage of LED product you would use to replace HID equipment. Review reported PPFD and check the mounting height associated with those measurements.The performance of light fixtures in a manufacturer's testing lab area may not be the same as the operational performance once installed on site.

PHOTO: CONSUMERS ENERGY

Find the Right Fit - Review performance metrics to sort and eliminate fixtures by intended use, rated lifetime hours, form factor, light distribution, flux output, *flux depreciation*, and warranty terms. Flux depreciation test results help you understand how long a light fixture can maintain light output[33]. Understand the useful life of products; LEDs can run for >50,000 hours according to most manufacturers. Along with reviewing performance metrics, check for warranty information to plan for the end of the product's service life. Inquire about equipment materials and what to do with components if they fail or break.

Read the Rainbow - Consult SQD graphs of various LED light fixtures to understand your options and determine the best fixture for the spectral treatments aligned with your cultivation approach. Consider whether you need or want light fixtures with a fixed or tunable spectrum. Since greenhouse lighting is supplementing sunlight, lighting system spectral choices are not the only input determining quality characteristics and driving biomass production.

Figure 11: DesignLights Consortium Designation for Lighting Products Listed on the Horticultural QPL

Purchase Certified Equipment - Independent organizations can help you select equipment certified to meet minimum technical requirements set by subject matter experts. The DesignLights Consortium (DLC) is a non-profit organization that qualifies the performance of high-performance lighting technology like horticultural LED light fixtures and lamps. Look for the DLC logo when reviewing product specification sheets, see Figure 11 at left. Growers who may not trust LED fixtures can find peace of mind in the third-party assurance of quality that DLC qualification can provide.

Understand Technical Requirements - The DLC develops technical requirements for horticultural lighting products and qualifies equipment to be included in their Horticultural Qualified Products List (QPL). Fixtures listed on the Hort QPL must meet equipment testing and reporting and thresholds for minimum photosynthetic photon efficacy (PPE), flux maintenance, component lifetime, and warranties. All manufacturers must submit their products to be tested by a third-party laboratory to be considered for qualification. Performance and lifetime claims are evaluated through third-party photon efficacy, photon flux, flux maintenance, and safety testing reports[34].

Verify Quality - Look for independent verification of quality claims made by light fixture manufacturers. Request and review the UL 8800 safety test reports produced by certified laboratories like CSA, Intertek, and TUV. Code officials may enforce special requirements upon facilities operating equipment not rated by national testing labs[35].

Anticipate Updates - The DLC will be issuing a draft for Version 3 (V3) of the Horticultural Technical Requirements in early 2022. The timeline for when V3 would come into effect is still being determined. An increase in the minimum acceptable efficacy is being considered. Efficiency programs may use the Hort QPL for LED lighting systems when specifying eligible equipment for their CEA programs.

Use Product Libraries - Products that meet the required performance criteria can be added to the QPL. In 2021, DC-powered fixtures, externally supplied actively cooled (including liquid-cooled) horticultural fixtures, and LED replacement lamps were added to the QPL. In March 2022, the Hort QPL offers programs and cultivators over 650 fixtures that meet the criteria outlined in the DLC Horticultural Technical Requirements V2.1. The Hort QPL is available online at designlights.org/qpl/hort.

Maximize Incentives - Efficiency programs in 35 states support **efficient horticultural lighting equipment**[36]. 275 programs in regions across the nation offer specialized horticultural lighting incentives. The average rebate for a 600 W LED fixture replacing a 1,000 HPS fixture is approximately $160 in February 2022, to offset fixture

33 ANSI/IES LM-90-20, Measuring Luminous Flux Waveforms for Use in Temporal Light Artifact (TLA) Calculations, 2020.

34 ANSI/IES LM-79, Approved Method: Optical And Electrical Measurements Of Solid-State Lighting Products, 2019, ANSI/IES LM-80, Approved Method: Measuring Luminous Flux And Color Maintenance Of LED Packages, Arrays, And Modules, 2020, In-Situ Temperature Measurement Tests (ISTMT), and ANSI/CAN/UL 8800, Standard For Horticultural Lighting Equipment And Systems, 2019.

35 A list of nationally-recognized testing labs (NRTL) is published by the Occupational Safety and Health Administration (OSHA) at https://www.osha.gov/dts/otpca/nrtl/nrtllist.html.

36 DLC Member Incentive Program Summaries (Horticultural Lighting), 2022.

costs of $900 - $1,000 per fixture. Contact programs early in design to understand requirements for incentives and understand how high-performance fixtures with high PPE can receive custom financial support. Efficiency programs may use the DLC Hort QPL of LED lighting systems when specifying eligible equipment for their CEA incentive programs. Do not assume that a DLC-listed fixture automatically qualifies for rebates and check with your efficiency program partner before purchasing any equipment. Share lighting design details with utilities and efficiency programs so they can calculate your facility's energy savings and custom financial incentives. In some regions, growers can receive rebates for horticultural lighting through rebate programs that do not require energy modeling.

Install LED Lighting in CEA Facilities

Once you have ordered your fixtures, it is time to put everything together properly to influence the indoor environment your crops will experience.

Wire for the Future - When installing light fixtures capable of dimming, ensure to connect dimming controls when installed, as retrofit costs can be substantial. Future-proof systems for new technology and controls functionality. Consider installing some extra fixtures in cultivation spaces or have extra fixtures stored on hand for maintenance or fixture failure.

Check Products - After lighting equipment is delivered but before fixtures are hung, perform some *prefunctional tests* to ensure it is the right product and does not have manufacturing defects. Use calibrated metering equipment to measure spectral treatments. *Quantum meters* that visualize spectra can be more expensive and cost-prohibitive for every facility to have one on hand. Send them to a separate lab that can verify the spectral treatment of the products you have received. Otherwise, there's nothing you can do if you find a problem.

Mount Fixtures - Influence PPFD received at crop canopy levels by optimizing mounting height. Consult manufacturer specification sheets to understand recommended mounting height for the fixtures you have purchased. Cultivation operations may choose to use movable fixtures or adjustable shelving heights to raise or lower light levels. Growers also use dimming controls to modulate the light output of fixtures and achieve target PPFD. Consider how adjustable fixtures and dimming controls could be applied in your facility to maintain light levels throughout the growth cycle of your crops.

Figure 12: Quantum Meter for Field Measurements

Verify Initial Light Levels - Measurement of PPFD is crucial and all growers should own at least one type of calibrated quantum sensor. Once you install your light fixtures and move your plants into your cultivation spaces, use calibrated metering equipment to measure average PPFD across the canopy. Figure 12 above shows a quantum meter displaying light level readings in units of μmol/s. Quantum meters have reduced in price in recent years and costs range from $200 to $800. Newer models can provide spot readings, log readings and display DLI and photoperiod data onscreen. Lower-cost equipment may be less accurate, measure fewer parameters, provide no logging, and need to be calibrated[37] more often. Greenhouse growers should

[37] Calibration drift, for sensors that are not damaged, is typically less than about 0.5% per year. The Clear Sky Calculator tool is a free calibration tool provided by Apogee, one of the leading manufacturers of quantum meters.

measure PPFD at different times of day and during different seasons, in particular at the time of year when DLI is at its lowest, as DLI changes significantly throughout the seasons.

Measure Right - Growing anything under electric lights without frequent measurement of photon flux is like trying to drive a car without a speedometer. Measure PPFD when plants are brought into the room and throughout production. Taking a PPFD reading directly below a light source is not representative of the entire grow room. PPFD should be measured in multiple places at a consistent elevation aligning with crop canopy height or at the grow media (for shorter crops). Take readings with a quantum meter in an evenly spaced grid layout so that values can be averaged across the canopy area and compared to the target PPFD for the plants' growth cycle. Measure in enough locations so that your average is statistically significant.

Place Sensors - Install sensing equipment to track and report environmental conditions like PPFD and DLI to observe changes between harvests. Use light sensors to inform the operation of your light fixtures and automate light schedules and modulate fixture intensity. Consider where you will place sensors to calculate sunlight received by the crop canopy. Sensors should be placed in a location reflective of the measurements the grower wishes to control. Sensors placed by the door or well above the canopy will not accurately reflect what is happening at the canopy level or within the canopy itself. Greenhouse weather stations should be placed out of direct sunlight and close to the facility, so sunlight readings are representative of the location. It is especially important for greenhouses to observe how light transmission changes as coverings age.

Integrate - Connecting lighting controls with other horticultural systems like environmental controls for HVAC equipment can be beneficial for optimizing target conditions for plants and energy efficiency. As plants receive light and water and transpire, affecting temperature and humidity, communication between systems allows for better coordination. Work with design and construction partners to understand which systems will inform each other and how equipment can be staged for precise control and low operating costs.

Validate Performance - Work with partners like commissioning agents to create *functional performance tests* to verify lighting systems can achieve goals established in design. In project documents, specify the equipment that should be used for measuring lighting parameters like PPFD and spectral treatment. Some tests that Lighting Working Group members recommend include ensuring that light fixtures provide expected light levels at full power, shut off completely, dim all the way up and down, and have output stay stable without flickering.

Commission Well - Ensure that commissioning agents test equipment only when all systems are on-site, hooked up to power, started up, and configured by the manufacturer or your construction contractors. Reserve enough time for site visits on several days at different points in construction and instruct construction partners to resolve issues identified in commissioning reports. Have tests performed both before and after plants are in the room. Employ an integrated commissioning plan that stress-tests lighting and environmental controls equipment in concert to stage equipment and observe interactive effects and appropriate responses.

Review Reports - Your contractors and consultants should provide final reports to summarize the testing they performed to validate the equipment can satisfy your design parameters. Ensure you request these documents and read them completely to follow up on issues identified within, as it is much more expensive to resolve problems once your building is occupied and operational. Have final reports include average PPE and PPFD of each of your cultivation spaces. Verify that fixtures are running at the temperature your project team forecasted in design. Understand that measurements may have a +/- 5 - 10% error band. Visual maps of spaces as lit can help operations and maintenance staff troubleshoot when light levels or quality change or if energy costs from lighting shift in unexpected ways.

Operate LED Lighting in CEA Facilities

Once you are ready to grow in your new or renovated space, keep an open mind as you operate new equipment and document changes you make as you adjust your growing approach.

Document Everything - As staff implement Standard Operating Procedures, it is crucial that your team write down lighting schedules for posterity and as inputs for controls systems. Prepare for turnover or plan for continuous improvement as you research and develop new ways to increase yields or maintain consistent crop quality. Create tables of target PPFD for different crops and cultivation spaces so equipment can be adjusted or replaced accordingly.

Evaluate LEDs Alone and Over Time - If possible, try to evaluate LED fixtures in a grow room by themselves so you can observe how they influence the primary drive of plant growth and development alone. Run multiple trials to observe trends. Give your crops at least three cycles under the same conditions to understand impacts.

Continue to Monitor Light Levels - Vertical growers should consistently measure light levels at different points in the crop cycle because as your plants grow, they get closer to your lights and PPFD increases more so than in other cultivation approaches. Greenhouse growers benefit from ongoing field monitoring of light levels to complement the average DLI assumed in design. Measuring light levels yourself is important in verifying that dimming controls are functioning as intended.

Revisit Environmental Controls - Since LED lighting products can give off less heat than HID equipment, cultivation spaces may need to revisit setpoint ranges for temperature and humidity. Indoor facilities outfitted with LED fixtures may need to be air conditioned less than rooms using HID lights, and greenhouses may have to provide additional heat, depending on targets for environmental conditions. When HVAC loads change under LED lighting, plants transpire differently and it can be helpful to change watering controls as well. To learn more about temperature and relative humidity considerations when cultivating with LED lighting, and many more tips for operating HVAC equipment efficiently in your facility, check out RII's *HVAC Best Practices Guide for Controlled Environment Agriculture (CEA*. Other controls like irrigation and fertilizer quantities and schedules may also need to change; stay tuned for more information in RII's *Controls & Automation Best Practices Guide for Controlled Environment Agriculture (CEA)* publishing in July 2022.

Dim Down to What - The output of your LED fixtures may need to be reduced for your plants depending on growth cycle and various characteristics of your grow rooms, such as wall color, plant growth cycle, and plant spacing. When ramping up production, start at partial power and work up to full. Consider a 'dim and trim' approach if adjusting the mounting height of movable fixtures. As a portion of total system cost, it is relatively easy and inexpensive to break up rooms into zones and dim with LEDs. Manage demand and save money on utility bills using dimming controls. Adjust light levels incrementally to find the sweet spot of maximum productivity with minimum resource consumption. Utility energy efficiency programs can offer financial incentives for **dimming controls** that save energy.

Make One Change At A Time - Alter parameters individually and incrementally and document what changes you made and when, and for how long with both notes and pictures. By understanding the changes you make and their interactive effects, you can make informed observations on what impact your adjustments are having on your plants before making multiple changes at once. Regularly record photoperiod, temperature, relative humidity, and other important factors to benchmark your operation as you make changes.

Tweak and Peek - Switching from HID lamps to LED light fixtures will require adjustments to many elements of your cultivation approach, including watering, fertilizing, CO_2 levels, photoperiod, and grow room temperature and relative humidity setpoints. Adopt a 'tweak and peek' approach to observe how your plants respond to new lighting after making changes and before you make any more. An open and curious attitude is necessary for you to adjust your cultivation activities to match the needs of your plants under LED. According to RII's Lighting Working Group members, to maintain leaf temperature and VPD, growers should increase temperature setpoints by 7–8°F to make up for the difference in light fixture heat output[38].

Clean & Calibrate - Clean the faces of LED fixtures just like you would clean reflectors of HID fixtures. This ensures the maximum amount of light can be used by your crops. Calibrate your control equipment by taking PPFD readings with handheld metering equipment every 3 - 6 months to adjust the responses of your equipment to match its latest performance in the field. This also allows you to establish trends so that you can track the flux depreciation of your fixtures. Diodes and drivers of LED fixtures may fail and require component repair or replacement of entire fixtures.

Record Light Level Trends - When you drive your car for hundreds of miles and calculate your MPG, this is similar to the average PPFD that should be measured to inform grow room and greenhouse design. Growers may consider replacing fixtures after a 6 - 10% flux depreciation (which is when there can be a noticeable difference in yield). This reduction is not detectable by your eyes. This is why the DLC uses a Q90 lifetime value of 36,000 hours for fixtures to qualify for the QPL; this means qualified fixtures emit 90% of the photons as usable energy after 36,000 hours of operation.

Measure Facility Efficiency and Productivity

You can use a variety of metrics to track the success of your business. Tracking efficiency can complement measuring the productivity and quality of crops grown in CEA facilities.

Ask for Guidance - Talk with growers that use LED solutions and automated lighting controls and benefit from their experience to move quickly up the learning curve. Read case studies to understand how facilities like yours adjust Standard Operating Procedures to optimize facility performance. Join our network of CEA producers to connect with other cultivators and collaborate.

Continue Learning - Best practices continue to emerge for greenhouses and indoor farms growing food, floriculture, and medicinal crops. Access the RII catalog, attend live workshops, and watch recorded webinars and Tip Clips featuring subject matter expert speakers. Learn from our industry network of growers, equipment manufacturers, architects, designers, and construction professionals.

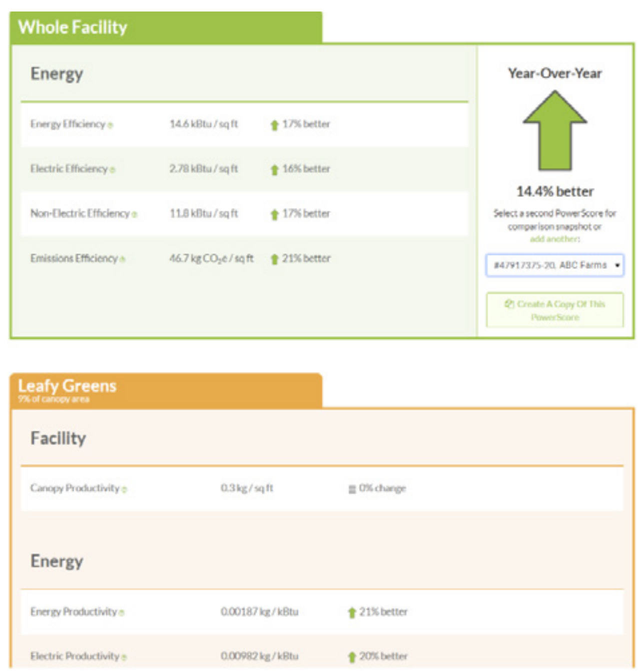


Figure 13: PowerScore Performance Snapshot and Lighting Key Performance Indicators

38 Opportunities in Controlled Environment Agriculture, Commonwealth Edison, 2021.

Benchmark and Compare - Calculate key performance indicators (KPIs) that matter most to your operation. While canopy productivity may be the greatest driver of revenue, resource efficiency and productivity affect your bottom line by impacting operational expenses. Benchmark your CEA facilities with RII's PowerScore resource benchmarking platform to measure and track the year-over-year trends in environmental KPIs for energy, water, and emissions. Figure 10 at left shows a Performance Snapshot for a vertical indoor facility, comparing two years of facility data. Examples of KPIs PowerScore calculations include Lighting Efficiency (measured in units of energy consumed per day by lighting systems) and Canopy Productivity (measured in units of biomass per units of canopy area).

PHOTO: VERTICAL HARVEST FARMS

Resources

Organization	Resource	Description	Link
Resource Innovation Institute	Utility Working Group	Landing page for RII Utility Working Group information and resources.	https://resourceinnovation.org/utility
	Catalog of Resources	Catalog of RII's published curriculum and training.	https://catalog.resourceinnovation.org
	Workshops and Webinars	Library of RII's live and recorded Efficient Yields educational workshops for CEA producers.	https://catalog.resourceinnovation.org/category/efficient-yields-workshops
	Best Practices Guides	Library of RII's peer-reviewed and brand-agnostic best practices guidance on efficient technology and approaches.	https://catalog.resourceinnovation.org/category/best-practices-guide
	PowerScore	RII's specialized resource benchmarking platform for controlled environment agriculture production facilities. PowerScore generates KPIs for resource efficiency and productivity of energy, water, emissions, and waste.	https://resourceinnovation.org/powerscore https://powerscore.resourceinnovation.org/go-cea
DesignLights Consortium	Horticultural Technical Requirements	Database of third-party certified LED light fixtures suitable for horticultural applications.	https://www.designlights.org/our-work/horticultural-lighting/technical-requirements/
	Horticultural Qualified Products Library	Database of third-party certified LED light fixtures suitable for horticultural applications.	https://www.designlights.org/horticultural-lighting/search/
	Member Incentive Program Summaries	A comparison of horticultural lighting program offerings and incentive levels across DLC Member territories.	https://www.designlights.org/resources/reports/dlc-member-incentive-program-summaries-horticultural-lighting/
Greenhouse Lighting & Systems Engineering	GLASE Lighting Short Courses	Plant Lighting Short Course in partnership with Greenhouse Lighting & Systems Engineering (GLASE), OptimIA, and Lighting Approaches to Maximize Profits (LAMP)	https://glase.org/plant-lighting-short-course/
University of Arizona	University of Arizona CEA Short Courses	Greenhouse Production & Engineering Design Short Course presented by the University of Arizona Biosystems Engineering Controlled Environment Agriculture Center	https://ceac.arizona.edu/events/cea-short-course
University of Arizona, Ohio State University, Michigan State University, Purdue University	OptimIA Indoor Ag Science Cafe	Supported by USDA and NIFA	https://scri-optimia.org/cafe.php

Organization	Resource	Description	Link
U.S. Department of Agriculture NRCS	Urban Agriculture Resources	NRCS conservation assistance is growing along with it. NRCS provides technical and financial assistance for assistance for urban growers in areas such as: soil health, irrigation and water conservation, weeds and pests, and high tunnels.	https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/landuse/urbanagriculture/
U.S. Department of Agriculture NIFA	Urban, Indoor, and Emerging Agriculture	NIFA supports research, education, and extension activities for facilitating the development of urban, indoor, and other emerging agricultural production, harvesting, transportation, aggregation, packaging, distribution, and markets.	https://nifa.usda.gov/program/uie-ag
	Lighting Approaches to Maximize Profits (LAMP)	Research and outreach project funded by USDA NIFA SCRI with the goal of maximizing profits by improving lighting systems used in controlled environment agriculture (CEA) by helping growers get more value out of their lighting systems by providing horticultural and economical information and tools to manage the lights for optimal crop growth and quality and to maximize the return on investment.	https://www.hortlamp.org/
U.S. Department of Agriculture ARS	Virtual Grower	Virtual Grower can help identify energy savings through different greenhouse and indoor farm designs, predict crop growth, assist in scheduling, make real-time predictions of energy use, and see the impact of lighting on plant growth and development.	https://www.ars.usda.gov/midwest-area/wooster-oh/application-technology-research/docs/virtual-grower/
U.S. Department of Energy	50001 Ready for Utilities, Implementers, and Energy Service Providers	50001 Ready recognizes facilities that implement an ISO 50001-based energy management system – a self-paced, no-cost way to build a culture of continual energy improvement. DOE partners with utilities and other organizations to support the program's implementation, often as part of an SEM offering.	https://betterbuildingssolutioncenter.energy.gov/iso-50001/50001Ready/50001-ready-program-utilities-admin-implementers https://betterbuildingssolutioncenter.energy.gov/sites/default/files/DOE_50001-Ready_Cohort.pdf

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RESOURCE INNOVATION INSTITUTE

Resource Innovation Institute is an objective, data-driven non-profit organization whose mission is to measure, verify and celebrate the world's most efficient agricultural ideas. RII's performance benchmarking service, PowerScore, enables cultivators to gain insights about how to reduce energy expenses and improve their competitive position. Resource Innovation Institute is funded by foundations, governments, utilities and industry leaders. For more information, go to ResourceInnovation.org.