RESOURCE INNOVATION INSTITUTE

LED LIGHTING FOR CANNABIS CULTIVATION

& CONTROLLED ENVIRONMENT AGRICULTURE

BY GRETCHEN SCHIMELPFENIG, PE

Part of RII's Resource Efficiency Best Practices Series

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A report from Resource Innovation Institute

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Available online at: www.ResourceInnovation.org/Resources

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OVERVIEW

As a cultivator operating in a constantly evolving industry, **you may feel like it is hard to know who to trust**. The horticultural market has changed a lot, technology has advanced, and so have the technical terms used to describe everything. It can be hard to navigate the purchasing process when planning a facility and challenging to understand minimum performance requirements for equipment.

We are here to help. As a non-profit organization, the Resource Innovation Institute establishes industry standards, facilitates best practices, and advocates for effective policies and incentives that drive resource efficiency. 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 cultivation facility may be detailed, but **it does not have to be a mystery**. Our membership is comprised 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 indoors.

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 energy 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

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 LED Lighting Best Practices Guide is to support you, the cultivator, and your design, construction, and operations professionals in:

- Speaking the language of horticultural lighting
- Reviewing manufacturer's literature to evaluate your purchasing options
- Understanding crucial considerations when selecting LED lighting
- Installing and operating successful LED lighting solutions in alignment with your business model

Your Grow, Your Way

There are three major styles of cultivation that can drive your considerations when making lighting decisions:

- *100% electric lighting*
  - Single level indoor
  - Vertically stacked indoor
- *Supplemental electric lighting*
  - Single level greenhouse

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 the indoor or greenhouse environment.

Demystifying Terms

As a grower navigating design, construction, and operations decisions, there are often different people telling you contradictory things, too many technical terms, and lots of jargon. You may be struggling with understanding how to take field measurements and why they are important to you, or how to use manufacturer and facility information appropriately.

Throughout this guide, you'll 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 terms to expand your horticultural lighting vocabulary: https://resourceinnovation.org/resources/lighting-terms

INTRODUCTION TO LED LIGHTING

The plants you grow are as unique as your growing approach.

Over the years, you may have used a few different types of lighting options, and may have tried a light-emitting diode (LED) light fixture to see how it could work for your plants. High intensity discharge (HID) lighting options like metal halide (MH) or high-pressure sodium (HPS) may be part of your tried and true solution for cultivation.

While HID lighting applies a standardized approach and may have served you well for a long time, **today's LED offerings are worthy of your consideration**. If you tried an LED product several years ago, you may be surprised by the reduced cost, improved quality increased output and improved performance, and wide variety of available products and approaches suited to best fit your needs.

While the marketplace has matured, **not all LED light fixtures are created equal**, and there are many options for you to choose. In recent years, organizations with deep expertise in lighting technology and quality have begun to certify qualified products to help growers discern products that have met technical performance requirements.

For every cultivation method, there is likely an LED grow light capable of meeting your needs.

Demand for a variety of lighting solutions and cost compression in cannabis markets have produced new attitudes about LED lighting, as growers **consider energy and resource efficiency to rise above the competition by reducing operations and maintenance costs through using high performance system**s. In some regions, standards and regulations for energy performance have emerged, and cultivators everywhere can benefit from understanding how LED lighting can be a tool for their facility's compliance and operational success.

BENEFITS OF USING LED LIGHTING IN YOUR FACILITY

Energy

- Use ~60% of the wattage of a typical HPS fixture
- Dimming provides plants exactly as much light as they need allows for additional energy savings
- Give off less heat; can downsize the minimum required capacity of your facility's HVAC equipment, lower first capital costs by as much as 33% as well as reduce recurring operating costs for air conditioning
- HVAC savings from smaller equipment can help fund higher upfront costs of LED lighting systems

Maintenance

- No bulbs to change
- Do not mind being cycled on and off
- Dimming prolongs life of equipment

Quality

- Longer predicted life than HID; can run for >36,000 hours while maintaining light output up to 90% of maximum output near end of life (LM90)
- Can provide adequate photosynthetic photon flux density (PPFD) for plants
- Flexible choices of spectrum can improve crop quality

Safety

- Ingress protection (IP) rating improves safety when applying sprays for integrated pest management
- No glass bulbs
- LED light fixtures do not contain mercury or phosphor; lowered risk of crop contamination upon breakage

? **A watt (W) is a unit that describes electrical power, and is used to describe the amount of power required to operate a device.** Labels on power cords for appliances may list maximum rated power, and normal operation can sometimes result in lower power draw in your facility. However, HID light fixtures may list rated power of the fixture, but the combination of a bulb and ballast along with the fixture may result in higher power draw than the rated power shown on the fixture's nameplate. Also, power demand for HID fixtures may increase over the lifetime of the lamp.

Wattage of equipment determines how much it will cost to operate your equipment, and the load taken by your electrical infrastructure. Running a 600 W LED light fixture for ten hours uses 600 W * 10 h = 6,000 watt-hours (Wh). Your electric utility charges you by the kilo-watt hour (kWh), which is one thousand watt-hours. 6,000 Wh = 6 kWh.

Watts are also described using units of *joules* per second. A *joule* is a scientific unit used to describe energy, and is used in metrics for light, including some defined later in this document.

Your electric utility may charge you for the *peak* demand of your facility each month; they may also charge you by the kilowatt (kW). 1 kW = 1,000 W. kW is used to describe peak demand, which can represent the power draw of your facility at the time of the month when the greatest amount of equipment was turned on or was running at maximum power, or a combination of both.

HOW PLANTS USE LIGHT

Humans and animals use light to see; the light that we interpret and every color in the world falls somewhere within the bounds of the visible light spectrum. Plants also use light – but as an energy source for shoot development, flowering, and pigmentation composition and as an input to sense environmental conditions.

To understand what matters most between plants and light, you can approach the topic from the plant's perspective.

Light is the primary source of energy your plants need for growth, and impacts development along with plant genetics, fertigation, and grow room environmental factors like CO^2, temperature, and humidity.

The following terms all relate to how plants use light as an energy source. Understanding them requires a bit of a learning curve, but is essential if you want to ask informed questions, make informed business decisions, and achieve an energy efficient operation, which can reduce operations and maintenance costs and improve your plant yield.

PAR: The Light Your Plants Use

Photosynthetically Active Radiation (PAR) is the light 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 measured in nanometers (nm); photosynthesis occurs between wavelengths of 400 nm (deep violet) to 700 nm (far red); recent studies suggest photosynthesis can be induced in wavelengths greater than 700 nm.

Light visible to humans ranges from 400 to about 600 nm. Some blue and red light outside of this spectrum can be challenging to see; some fixtures add a little green in the fixtures so that people can visually inspect the color of their plants more easily. PAR is not a unit, but a range of light energy that plants can use for their various growth cycles and biological processes.

? **PAR is not a unit, but a range of light energy that plants can use for their various growth cycles and biological processes.** PAR Can be confused with PPFD (defined below). Understand the difference to design the best environment for your plants. To understand how to measure the light that plants use for photosynthesis is measured, meet the micromole.

Micromoles: Particles of Light

A mole (mol) is a way to describe a quantity of light; it gives us a way to describe light as finite quantities of photons. A photon is a bundle of electromagnetic energy and is the basic unit used to describe light.

Because a single mol is a very large number, quantity of light is often described using the micromole (µmol). There are one million micromoles in a mole.

Once you are familiar with the units used to measure light, you have to be specific about what it is you would like to measure.

Understanding the difference between Photosynthetic Photon Flux (PPF) and Photosynthetic Photon Flux Density (PPFD) is as important as knowing the difference between length and square footage.

Photosynthetic Photon Flux, or PPF: Rate of Light Produced

Photosynthetic Photon Flux, or PPF, is the total amount of light (number of photons measured in micromoles) within the PAR range that a light fixture produces every second. PPF is not the amount of light your plants will receive in your facility. PPF is the amount of light your fixtures can produce between 400 and 700 nm.; this does not mean it is the amount of light your fixtures *will* produce, nor the amount of light that will reach the crop canopy.

A µmol is like a grain of salt and a mol is like a spoonful.

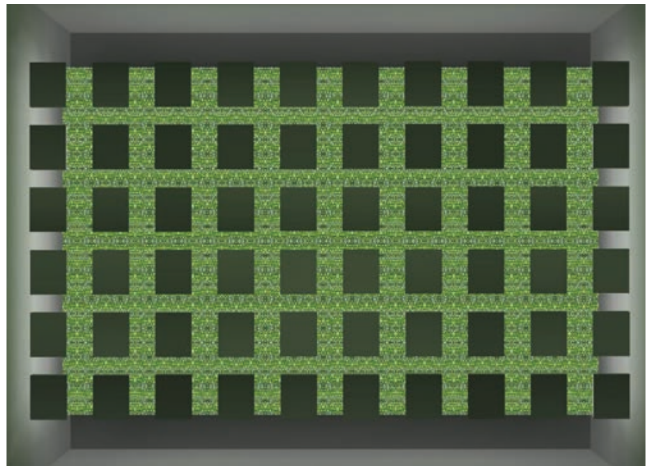
! **Lumens and PPF are similar. Lumens measure one type of light response for humans, so lumens are based on a spectrally weighted response for human vision.** This has created the turn of phrase "lumens are for humans." Just because a light fixture boasts a certain lumen output, that doesn't indicate the amount of photons that will be received by your plants; review PPF of various fixtures instead.

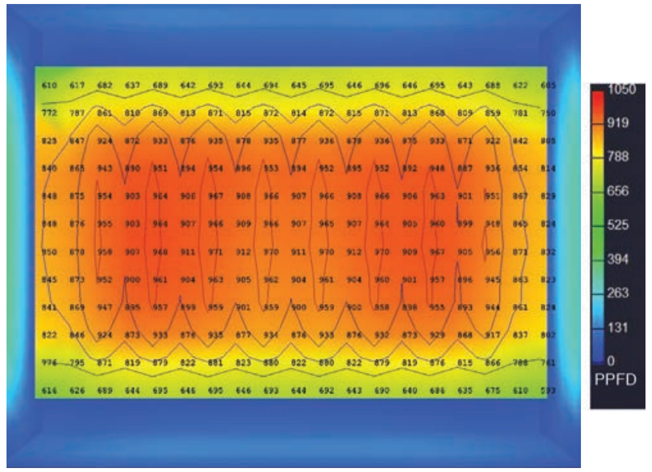
Photosynthetic Photon Flux Density, or PPFD: Light Received By Your Plants

Photosynthetic Photon Flux Density, or PPFD, is the amount of light (number of photons measured in micromoles) within the PAR range that hits a given area of plant canopy every second. PPFD measures the light your plants actually receive in your facility. 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.

Average PPFD should be used to inform facility design; in the field, PPFD measurements should be taken at multiple points evenly spaced across the plant canopy area (so that each point is measuring the same area) and then averaged and compared to the target PPFD for plants' growth cycle. The measurements at right show the PPFD values at various points under a fixture.

PPFD should be measured at a consistent height. The graphics at right show PPFD values modeled for a grow room at evenly spaced points at a consistent height. A grower can use their light meter to corroborate modeled readings in the field by measuring them at the same height as the model.





PPFD measurements at recommended mounting heights are provided by lighting manufacturers so growers know what their plants could receive in similar conditions. The graphic shows µmol received as modeled at evenly spaced locations across the plant canopy area.

? *Canopy area* is the total rectangular area of the entire plant canopy in a room, and represents the usable production space in your grow rooms. Canopy area does not include walkways.

! **Taking a PPFD reading directly below a light source is not representative of the entire grow room**. 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.

Photosynthetic Photon Efficacy, or PPE: A Fixture's Capability to Produce Light

Efficacy defines a light fixture's ability to convert power from electric energy and deliver photosynthetic photon flux (PPF) to your plants, It's important for you to know the efficacy of lighting solutions to understand the amount of photons your light fixtures deliver for their wattage. The metric used to measure PPE is micromoles per second per Watt, which simplifies to µmol/J, since a Watt is a Joule per second. PPE describes how much light a fixture produces from its input power.

PPE of a fixture listed by a manufacturer does not account for fixture arrangement, fixture type, or mounting height and distance from plants. While PPE is an important metric to rate fixture efficacy compared to other fixtures and estimate how it may operate in your facility, PPE does not reflect how many fixtures you will need in your facility to reach a target PPFD.

! **Many utilities qualify products with PPE at or above 2.0 µmol/J for financial incentive programs.** A typical Double-Ended 1000 W High Pressure sodium fixture has a PPE of 1.7 µmol /J.

! **Photosynthetic photon efficacy, PPE (the rate of light per electric watt), is similar to miles per gallon. Like MPG, PPE is just a rating and is not representative of your actual experience with installed equipment in the field.**

Daily Light Integral, or DLI: Light Received by Your Plants from the Sun

If you are cultivating in a greenhouse, it is important to consider how much sunlight your plant receives over the course of the day, and how those light levels may change throughout the day and seasons. If you are considering supplemental lighting for your greenhouse, measure the Daily Light Integral (DLI), the total PPFD inside the greenhouse on a gloomy winter day, or over several days throughout the seasons, and plan your strategy accordingly once you understand what electric lighting can offer for your operation.

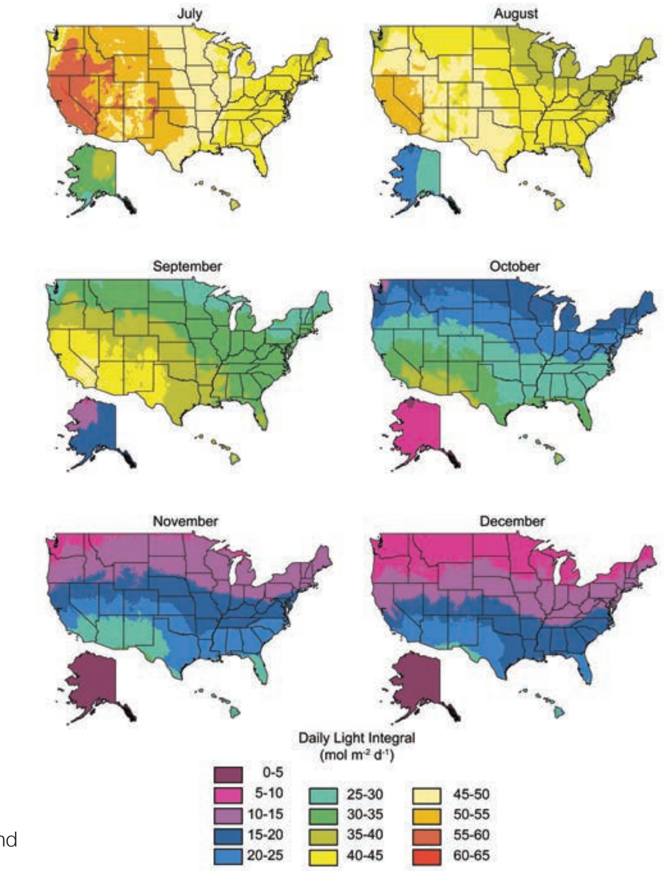
Instantaneous readings are very helpful for strategic planning of supplemental lighting strategies. DLI maps shown on this page at right convey long-term information, but do not predict what you will actually get on any given day.

! **Daily Light Integral (DLI) is the sum total of moles of photons per meter squared per day (mol/m2/d).** ***Note the differences in DLI in the same location between July and December. Compare the difference in DLI in the same month in varying climates across the United States.***

In the graphic, the average monthly DLI in Minnesota varies significantly from Arizona. Understanding DLI is critical to establishing an effective supplemental lighting strategy.

These average monthly DLI plots apply to field measurements. For greenhouses, a rough rule of thumb is that 30 to 50 percent of the daylight will be reflected by the greenhouse glazing. This will vary according to the material and age of the installation. The average monthly DLI inside the greenhouse will be correspondingly lowered by the proportion of reflected daylight.

An interactive version of these maps are available at https://webgis.coe.clemson.edu/storymaps/light-integral-map/. Note that DLI maps are currently available for the United States only.



Faust, J. E., and J. Logan. 2018. "Daily Light Integral: A Research Review and High-Resolution Maps of the United States," HortScience 53(9):1250-1257.

HOW PLANTS USE LIGHT SPECTRUM

Every part of the light spectrum can influence your plant. However, not all photons have the same impact. <u>Different wavelengths used in LED light fixtures do different things to your plants, and different cultivars can react differently to different spectra of light.</u>

You may be familiar with some of these parts of the light spectrum:

- UVB
- UVA
- Blue
- Green
- Red
- Far Red

White is the sum of all colors in the spectrum.

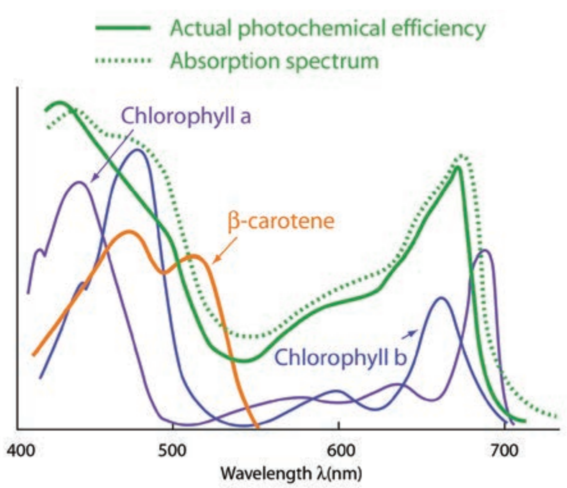
As technology develops and research continues, the cannabis industry is still learning what ranges of the light spectrum do to influence plant development, yield, cannabinoid concentration, presence and concentration of terpenes, and taste.

Understanding and Choosing Spectrum

Plants love sunlight; they evolved to use it for growth, so it is the perfect fit for their systems.

If you want to use artificial lighting (or, more appropriately, electric lighting), to drive growth you need to learn how to interpret the light spectrum and how different wavelengths are used by your plants.

If you want to intelligently select LED fixtures to provide electric light for your plants, you need to learn how to interpret spectral quantum distribution graphs so you can read the wavelengths being offered by light fixtures.



Plants primarily use wavelengths in the 400 to 700 nm range for photosynthesis; different components of plants' biochemistry use different parts of the spectrum. Moore, R., Clark, W. D., Kingsley, R. S., and Vodopich, D., Botany, Wm. C. Brown, 1995.

***Spectral quantum distribution 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, or color, in units of µmol/s/nm.

Spectrum matters, and not all spectra offer equal benefits to your plants.

HID lights offer different broadband spectra for different types of bulbs; you may already use them to your advantage. For example, it is common practice to use the blue-tinted Metal Halide (MH) spectrum for vegetative phase and the orange-red High Pressure Sodium (HPS) spectrum for the flowering phase.

LED products come in many different narrowband wavelength spectra and choice of broadband "*white*" spectra, making it possible for lighting companies to customize and fine-tune the lighting spectrum of their fixtures to suit your plant type, stage of growth, and desired quality characteristics. For even finer control, some tunable LED light fixtures allow the grower to adjust the intensity and spectrum produced to tailor lighting to specific cultivar growth stages.

Most LED lighting manufacturers have adopted spectra that look white to the human eye when designing fixtures for cannabis. White light includes the visible spectrum from blue through green and yellow to red (the entire 400-700 nm range); a rapidly evolving area of research is investigating whether white light is best for the flowering stage of cannabis.

Greenhouse growers: if you are choosing fixtures for supplemental light, the exact spectrum used is less critical than sole-source single level and vertical arrangements. The sun will provide the majority of the plant's light requirements, while the LED fixture will provide mostly daytime extension when the outside light is less than the desired photoperiod. Your photoperiod is the number of hours per 24 hour day in which your plants are exposed to light. Cannabis plants in vegetative growth stages typically require 18-hour photoperiods and in flowering stages need shorter photoperiods of 12 hours or less.

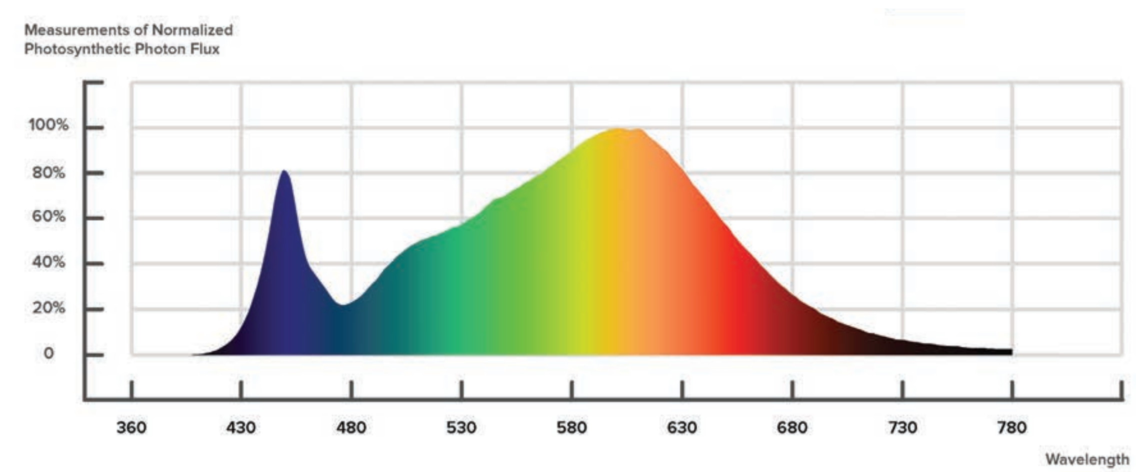
Since the sun is the dominant source of light for your plants, greenhouse growers will notice their plants react much less to specific spectra of the supplemental light source when compared to plants in sole-source cultivation environments.

Wide or full spectrum products can claim to mimic daylight; since the spectrum of daylight varies constantly, this description does not tell you enough information about how a light fixture will perform with your plants. Also, 'wide' can mean many things, and is relative between fixtures.

Compare spectral distribution graphs of sunlight to HPS, MH, and various LED lighting options available to you to understand the wavelengths your plants see under different light fixtures.

<u>Some parts of the spectrum should be considered with caution</u>. You may have heard of *blurple* lights in earlier stages of the LED market. Blurple is used to describe a combination of blue and red light, the most efficient wavelengths for photosynthesis. Blurple lights can function perfectly well in vegetative stages of growth.

However, some blurple light products produce a spectrum that has been shown to be problematic for the flowering cycle of cannabis in particular.



An LED light fixture's spectral quantum distribution graph.

UNDERSTANDING YOUR LIGHTING OPTIONS

You have many reasons why you may be learning about lighting and considering LED light fixtures for your facility. This section is organized to serve every grower at every stage of facility design and construction. Start at the top if you are designing a new facility or a major renovation project, and skip further down to learn about purchasing, installing, and operating LED light fixtures for retrofits. Whether you are an indoor or greenhouse grower, there are many considerations to take into account, and we are here to help you navigate your choices.

YOUR CULTIVATION APPROACH

Each of the three major cultivation approaches may use different types and form factors of light fixtures.

Form factor **is used to describe the shape of a light fixture. Form factor of your light fixtures 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, how the light is distributed at the canopy level, and how you run it to accommodate the unique aspects of your grow room or greenhouse.

Single Level Indoor

If you are a single level indoor grower, you use a typical 'warehouse' growing approach, where electric light fixtures are mounted anywhere from 3 to 10 feet above your plant canopy.

Traditionally, light for single level indoor grow facilities has been provided by a grid of HID fixtures. The single level growing approach was developed to maximize the effectiveness of HID lighting.

If you are a hybrid grower trying other lighting technology, you may have adopted a 'checkerboard' approach utilizing a combination of HID and other types of light fixtures, such as ceramic metal halide (CMH) or plasma.

Vertical Indoor

If you are a vertical grower, you use an approach modeled after vertical indoor vegetable growing facilities. Vertical indoor grows are relatively new, are challenging to design and operate, and are more expensive to set up per square foot than a typical single level indoor grow. However, your vertical indoor grow can use resources extremely efficiently and are worthy of consideration when retrofitting a facility from HID to LED light fixtures.

Your vertical indoor facility might use some LED lighting, as racked vertical growing arrangements are more feasible with LED fixtures since the light fixtures are mounted within 12 inches of the plants. HID lights generate more heat than LED fixtures; for this reason, LED solutions are more advantageous in vertical arrangements because they can be mounted very close to the plant, while HID arrangements might burn plant canopy in certain vertical layouts.

Vertical indoor racking is especially advantageous in jurisdictions that count 'canopy area' and not 'plant count' and a great way to maximize facility space efficiency, measured in grams of dried flower produced per square foot of your facility's floor area. The typical strategy in a vertical indoor facility is to run many smaller plants on a short vegetative (veg) cycle, which maximizes throughput and minimizes time and energy spent growing the plants in veg.

Greenhouse

If you are a greenhouse grower, you use an approach similar to a single level indoor grow. Form factor is still an important consideration, even though the solar position and shadows move throughout the day. Larger luminaires mounted close to the plant canopy may increased shading; thoughtful combination of form factor and mounting height can minimize shadow footprint. Variable lighting conditions can result in energy waste or under illumination in greenhouses. Control technologies that monitor DLI and modulate supplemental lighting can help you improve the operational efficiency of your greenhouse facility.

The cost of your lighting system can be substantially less, depending on geographical location, than an indoor operation, since the sun is your primary light source, and this means that output is likely less than an indoor grow.

Your greenhouse lighting system only needs to add supplemental light in cases of cloud cover or short days in the winter. You might use the same light fixtures to provide supplemental greenhouse lighting as an indoor grower. These fixtures are typically mounted high above the canopy, near the greenhouse 'gutter' height.

OPTIMIZING YOUR FACILITY DESIGN

The layout of your cultivation spaces substantially influences the lighting layouts and the form factors of LED fixtures available to you.

***Uniformity* of light levels is necessary for all of your plants to receive the same PPFD from your light fixtures.** Fixture spacing and mounting height contribute greatly to uniformity. For example, continuous runs of linear LED fixtures may improve uniformity compared to HID fixtures.

As you approach an LED lighting installation, 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 LED lighting systems that meet your expectations.

***Greenhouse growers designing supplemental lighting* should understand and use the average DLI during the lowest-light period of the year at your location** - usually December in the northern hemisphere, or June in the southern. This minimum average DLI helps you determine the amount of supplemental light required for your greenhouse spaces; you will be looking to provide daytime extension to ensure your desired photoperiod.

Determine Quantity and Spacing of Your Plants - Understand the number and layout of your plants in each cultivation space. Where are your walkways? *This will influence the actual PPFD seen by your plants and the spill light impact*. <u>Consistent spacing of fixtures and plants will result in more uniform light levels</u>.

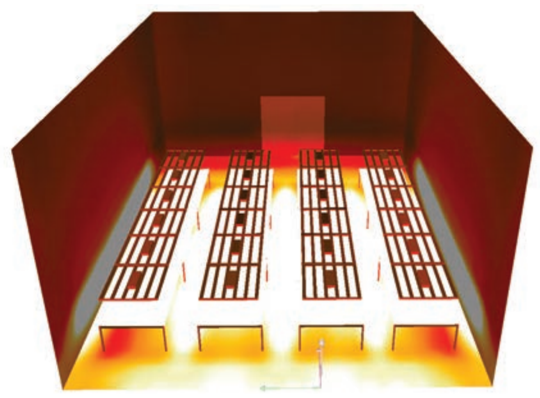
Quantify Your Grow Rooms - Determine the square footage of the areas in your facility that will be dedicated to different plant growth cycles. *This will influence the quantity of light fixtures under your consideration*.

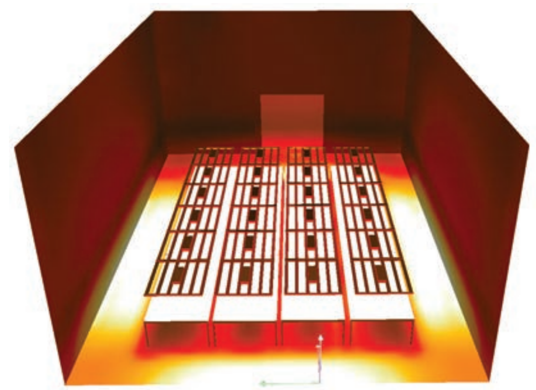
Describe Your Cultivation Approach - Consider how you grow; do you have an indoor or greenhouse facility? Single level or vertical grow? Will you be providing primary or supplemental lighting? *This can influence the form factor of the light fixtures you can consider, as well as the necessary light levels to be provided by your lights*.

Understand Interactive Effects - If your grow spaces were originally designed for HID lights, and you retrofit your spaces with LED lights, your HVAC equipment has less heat to deal with and can 'cycle' more rapidly, which could lead to temperature and humidity swings within your cultivation spaces. *Cycling is hard on your HVAC equipment and will reduce its useful life. Consider the interactive effects of lighting and HVAC systems and retrofit to LED light fixtures thoughtfully*.

Set Your Target PPFD Levels - Understand the ranges of PPFD necessary for your plants' growth. Many manufacturers of horticultural lighting offer free design assistance using lighting design software programs. Their plans offer estimated PPFD targets and uniformity, and can specify layouts so you can achieve your target PPFD.

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 requires more fixtures, or lower uniformity which can save you capital and operating dollars, as long as the canopy is getting what it needs*. Beware that low uniformity can lead to other problems: crop cultivation issues with nutrient and water usage, modified plant growth in size and shape, and at worst, variable yields.





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Spill light is used to refer to light delivered by fixtures used for growing that ends up on walls and walkways instead of being received by your plants. Your people need much less light than your plants.

Minimize Spill Light on Your Walkways - Efficient space utilization combines an understanding of spill light with a strategy to minimize walkway area. Growers should understand the PPFD at the canopy per square foot per watt; this can illustrate how efficiently cultivation space is utilized by telling you the amount of light being wasted on your non-plant spaces.

Check out the two graphics at left showing a cultivation space with rolling benches. The graphic on the top shows a baseline layout, and the graphic on the bottom shows an optimized walkway layout for a cultivation space. The space on the bottom maximizes the light energy received by plants.

PURCHASING EQUIPMENT FOR YOUR FACILITY

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.

Review Manufacturer Literature - Manufacturers' specification documents, known as 'spec sheets', 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.

Choose Your Form Factor - As you consult spec sheets, consider what form factor is most suitable for your various cultivation spaces.

!

Your growing approach will influence the form factor of LED light fixture you choose for the cultivation spaces in your facility.

Single Level Indoor- If you are retrofitting to LED light fixtures, the types of fixtures you might typically consider are LED fixture types with similar form factors and mounting heights to your existing HID lighting system.

If you want to modify your form factor or mounting height with your retrofit, there are also many high-output LED bars that can also be used for single level indoor applications.

Vertical Indoor- If you are retrofitting your facility to use LED light fixtures, now is a good time to think about going vertical.

For this arrangement, it is ideal to consider fixtures that have several 'light bars' spread light evenly in a short vertical area. This allows no one portion of the canopy to receive too much light or heat.

Greenhouse- If you are adding supplemental LED lighting to your greenhouse facility, consider the form factor of your fixtures.

Your light fixtures shade your plants from the sun. Consider smaller LED light fixtures like light bars LED light fixtures with form factors that minimize shading.

Compare Apples to Apples - 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.

Find the Right Fit - Review performance metrics to sort and eliminate fixtures by intended use, rated lifetime hours, distribution, flux output, flux depreciation, and warranty terms. Flux depreciation performance metrics help you understand how long a light fixture can maintain light output (like the 90% output described by LM90 test results).

Read the Rainbow - Consult spectral power distribution graphs of various LED light fixtures to understand your options and determine the best fixture for the spectral preferences aligned with your cultivation approach. Consider whether you need or want light fixtures with a fixed or tunable spectrum.

!

Spectral power distribution graphs are less critical of a consideration for greenhouse growers; since greenhouse lighting is supplemental, the spectrum you choose will not determine morphology or chemovar nearly as much as an indoor grow where lighting is the sole source of nutrients for your plants. Some greenhouse growers in sunny regions install lighting with lots of red and blue in their spectrum for day extension to maximize efficiency.

Verify Quality - Independently verify quality claims made by light fixture manufacturers by reviewing the safety test reports produced by certified laboratories like UL, CSA, Intertek, and TUV. Code officials may enforce special requirements upon facilities operating equipment not rated by national testing labs. 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.

SELECTING THIRD-PARTY CERTIFIED LIGHTING EQUIPMENT

Independent organizations can help you select equipment certified to meet minimum technical requirements set by subject matter experts. More standards and product labels from other organizations are anticipated to emerge as the market matures.

! Look for the DLC logo when purchasing LED lighting. The DesignLights Consortium (DLC) is a non-profit organization that sets standards for LED light fixtures.

The DLC develops technical requirements for horticultural lighting products and evaluates equipment to be included in their Horticultural Qualified Products List (QPL). Technical requirements include thresholds for efficacy (PPE), Photon Flux Maintenance, warranty, safety certification and minimum driver and fan lifetime hours. All manufacturers must have their products tested by a third party to be considered for qualification. Performance and lifetime claims are evaluated using this third party LM-79, ISTMT, and safety testing and products that meet the required performance criteria are then listed on the QPL. Note that bulbs, DC-powered and liquid-cooled fixtures are currently not eligible.

Growers who may not trust LED fixtures due to prior negative experiences with poor quality products not well designed for cultivation applications can find peace of mind in the third-party assurance of quality that DLC certification can provide. Consult the DLC Horticultural QPL to find LED light fixtures that have been verified for durability, light quality, efficacy, and energy consumption. The QPL is available online at https://www.designlights.org/horticultural-lighting/search/.

Utilities offering energy efficiency programs for LED lighting for cultivation may require growers to purchase DLC-certified light fixtures in order to receive financial incentives.

INSTALLING LED LIGHTING IN YOUR FACILITY

Once you have ordered your fixtures, there are a few more considerations that can influence the indoor environment your plants will experience.

Consider Fixture Spacing - One of the two major factors influencing PPFD received by your plants is the horizontal spacing of your light fixtures. Try to ensure consistent spacing in both X and Y directions in your cultivation space to maximize uniformity. LED manufacturers will provide suggested spacing and mounting heights in their lighting layouts. Work with your selected lighting manufacturer to verify the installation recommendations for your cultivation spaces.

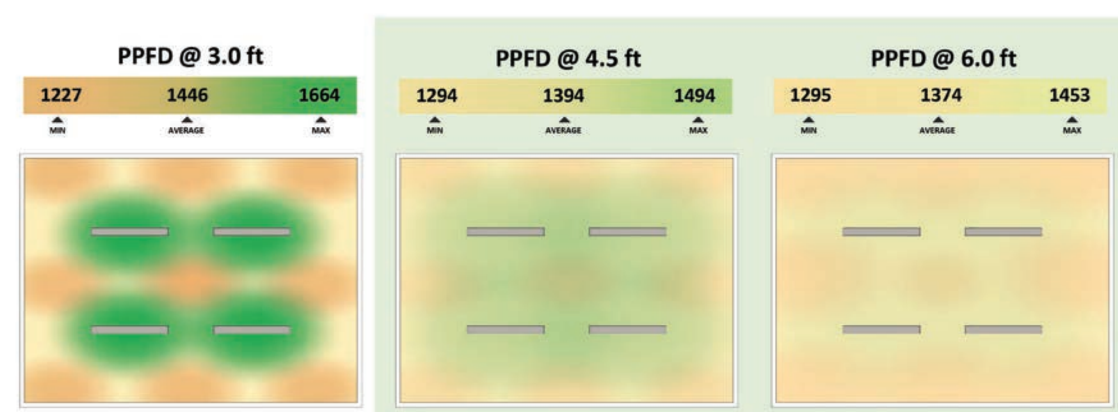
Determine Mounting Height - The second major factor influencing average PPFD seen at the plant canopy. Consult manufacturer specification sheets to understand recommended mounting height for your selected fixtures. The PPFD documented in spec sheets should report an associated mounting height. Consider adding two options to maintain light levels through the growth cycle: 1) adjustable mounting heights for fixtures or shelves. 2) adjusting light levels through lighting controls (dimming and trimming) with LED technology.

Choose Your Wall and Ceiling Colors- Minimize spill light and maximize PPFD by using white walls and ceilings. Light-colored finishes are also best for cultivation spaces to optimize energy efficiency.

Measure Light Levels - Once you install your light fixtures and move your plants into your cultivation spaces, use a calibrated PAR (quantum) meter to measure average PPFD across the canopy. Greenhouse growers should measure PPFD at different times of day and during different seasons, in particular at the time of year when DLI is at its lowest.

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 than in other cultivation approaches. As your plants acclimate to higher intensity light, this can boost growth but can reduce uniformity. Higher light intensity can be a problem in grow rooms where light levels are already too high, so dimming may be required. Measuring light levels yourself is an important step in verifying that dimming controls are functioning as intended.

! To accurately measure average PPFD in the field, take readings at canopy level rather than directly under your lights to understand the light energy your plants are receiving at their current stage of growth cycle. 'Canopy level' varies in the field and is averaged across the tops of many plants in the space.



This graphic shows minimum, average, and maximum PPFD in a grow room with four linear fixtures, with PPFD measurements taken at three different heights: 3, 4.5, and 6 feet above the ground.

OPERATING LED LIGHTING IN YOUR FACILITY

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.

Ask for Guidance - *Switching from HID lamps to LED light fixtures will require adjustments to many elements of your cultivation approach, including watering, fertilizing, CO2 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.*

Talk with growers that have moved to LED solutions and benefit from their experience to move quickly up the learning curve. This is where the Resource Innovation Institute can help. Attend Efficient Yields, our grower education events, and workshops directed by RII subject matter experts to learn from our industry network of manufacturers, designers, and installers. Join our grower network to connect with other cultivators and get your questions answered.

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.

Evaluate LEDs Alone and Over Time - If possible, try to evaluate LED fixtures in a grow room by themselves; remember that you are changing the primary source of energy used by your plants. Run multiple trials; give your plants at least three cycles under the same conditions to understand impacts.

Record Light Level Trends - Record data over time to establish trends so that you can track the flux depreciation of your fixtures. Growers may replace fixtures after a 6-10% depreciation of PPFD (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.

Control Output with Dimming - Start at partial power and work up to full. 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.

Revisit Temperature and Relative Humidity Setpoints - Since LED products can give off less waste heat than HID equipment, your grow room can be air conditioned less than rooms using HID lights, and you may need to provide additional heat to your plants, depending on your grow room temperature setpoint. Your relative humidity settings for cultivation spaces may need to change when you move to LED light fixtures, as the dynamics of heating the canopy are changed with the reduction in heat. Your plants' transpiration pattern is different, especially when your lights turn off and on, due to the absence of the infrared radiation that is produced by HID lights.

> **!** **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 our **HVAC Best Practices Guide.**

MEASURING YOUR FACILITY'S OPERATIONAL EFFICIENCY

You may be using a variety of metrics to track the success of your business; different companies track this differently, but all should be tracking efficiency.

How do you measure the efficiency of your operation?
You may have heard quite a few metrics before, like pounds per light fixture, pounds/plant, or grams/watt, but none of these are accurate measures of your operational efficiency.

Refer to our Cannabis PowerScore to learn more about how the Resource Innovation Institute can help you measure and track the efficiency of your facility.

Additional Resources
Check out our case studies online at **www.ResourceInnovation.org/Resources.**

> **?** Facility energy efficiency is the ratio of production of dried flower in grams to whole building energy consumption in thousands of Btu (kBtu) per square foot of flowering canopy area. Flowering canopy area uses the most energy out of all spaces in your facility, and therefore is the best way to normalize the facility's overall energy use intensity.

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RESOURCE INNOVATION INSTITUTE

The Resource Innovation Institute (RII) is a non-profit organization whose mission is to advance resource efficiency to cultivate a better agricultural future. RII provides best practices guidance on resource efficient cultivation technologies and techniques via peer-reviewed reports and curated events. RII's performance benchmarking service, the Cannabis 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.