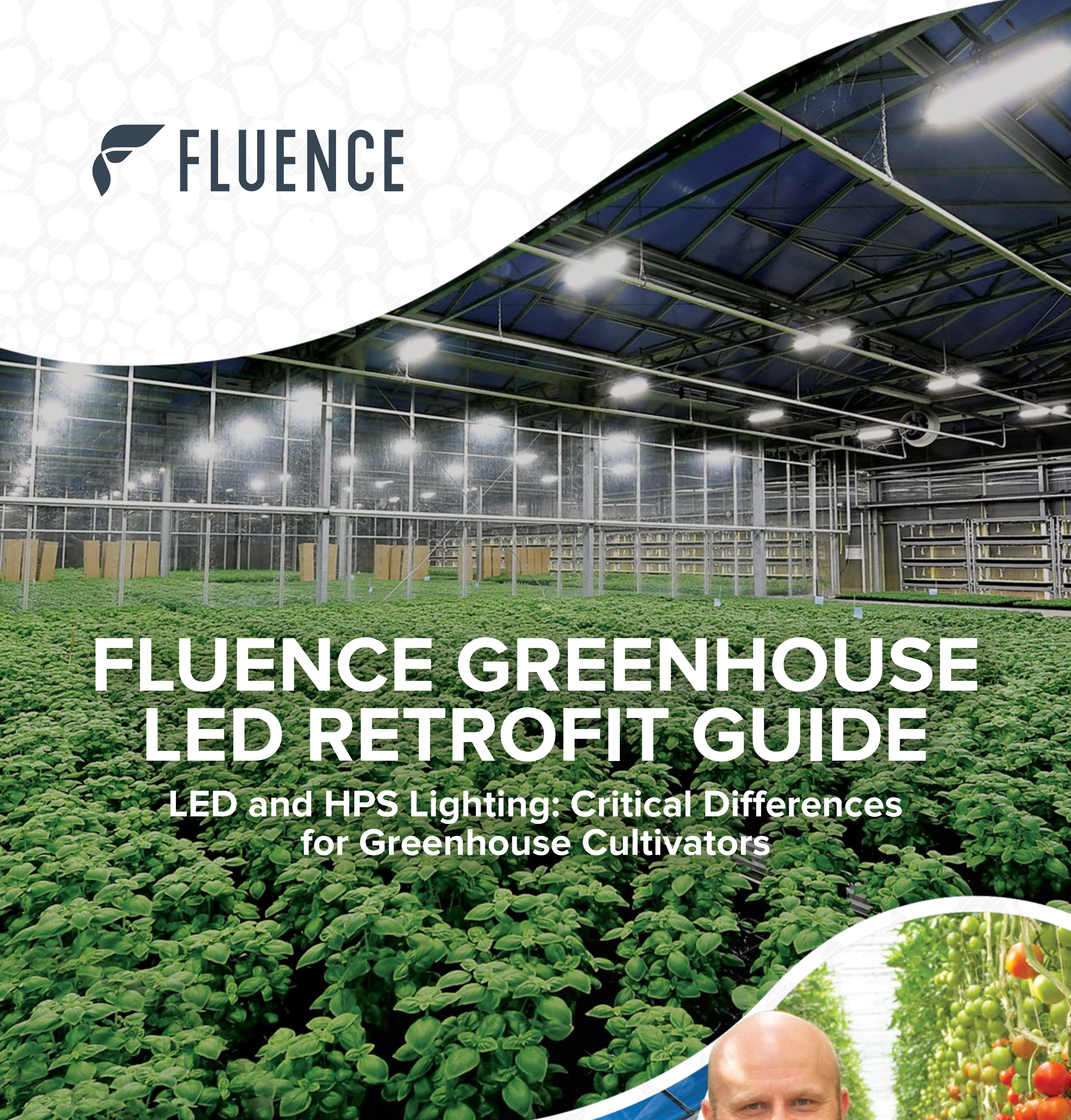
FLUENCE



FLUENCE GREENHOUSE LED RETROFIT GUIDE

LED and HPS Lighting: Critical Differences for Greenhouse Cultivators

In the early 2010s, light-emitting diodes (LEDs) emerged as a commercially-viable alternative to high-pressure sodium (HPS) lights for controlled environment agriculture. Now, LED systems cost less than ever and yield unprecedented benefits that are driving their widespread adoption.

Retrofitting a greenhouse with LEDs does more than reduce electrical costs — it fundamentally changes environmental control and enhances season-to-season lighting capabilities. Because LED fixtures produce less heat than HPS lamps of similar light output capacity, they bring systemic benefits to the greenhouse that ultimately increase yield and crop marketability.

In this guide you will learn:

- The surprising factors affecting your LED system's ROI
- How LEDs decrease — and increase — energy consumption for lower costs overall
- Why LEDs enable increased PPFD throughout the warmer months
- How to take the next steps in your analysis of an LED retrofit

LEDs Provide More Control

With HPS, space heating is strongly correlated with light production because the HPS spectrum contains significant radiant heat. Even in environments with additional heating needs, electrical heat from HPS lamps proves a costly way to meet the need.

LED fixtures — which produce less heat per photon than HPS lamps — grant cultivators revolutionary control over their environment. By decoupling light from heat, LEDs can mitigate variations in temperature, humidity, and carbon dioxide (CO_2), as explained in this guide.

LEDs Provide More Light Annually

Because of their lower operating temperatures, LEDs permit supplementation in the warmer seasons of spring, fall, and even summer. The resulting increase in light assimilation boosts annual yield. Moreover, the dimming capabilities of LEDs enable daylight harvesting, lowering costs by delivering light more precisely and consistently.

Understanding the cultivation dynamics of LEDs will enable stakeholders to make sound decisions when working with consultants and lighting manufacturers to replace HPS lights. While no two greenhouse applications are identical, the concepts described in this guide lay the foundation for a successful LED retrofit or LED/HPS hybrid integration.

Managing Heat for Better Harvests

LEDs convert electricity into photosynthetically active radiation (PAR) more efficiently than HPS lamps. Commercial LEDs achieve 2.7-3.8 micromoles (µmol) of photons per joule (J) while HPS fixtures seldom exceed 1.8 µmol/J. This increased efficacy — an improvement of more than 50% — gives cultivators the option of reducing their energy use or raising their lighting capacity by matching the wattage of their legacy HPS system.

Either way, LEDs generate less by-product heat per photosynthetically active photon than HPS. Some cultivators value the inefficiency of HPS lights because the high infrared (IR) output helps them meet their heating needs. However, heat generated from electrical lighting is usually more expensive than combustive heat sources.

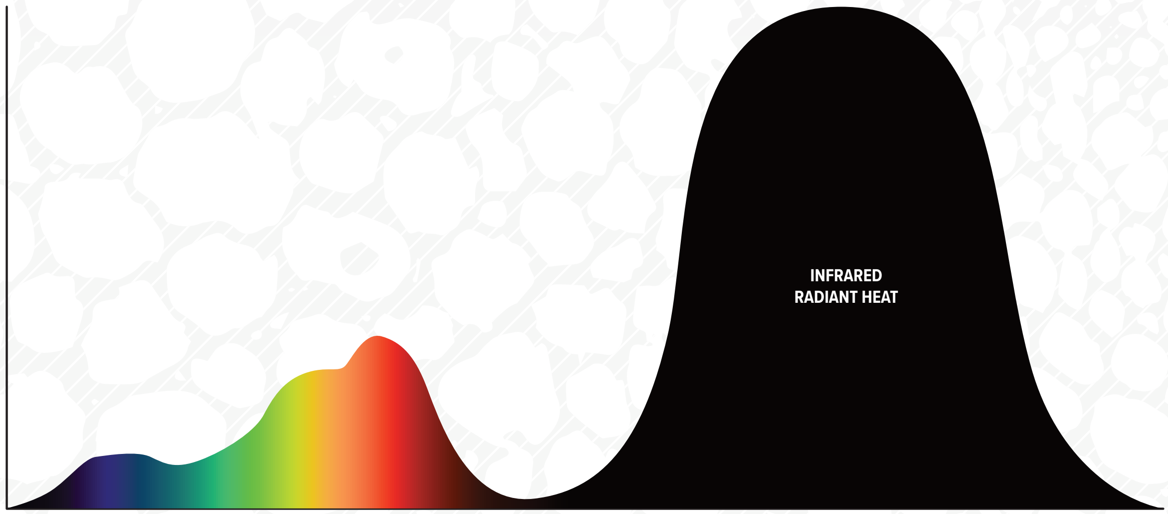
The trickle-down effects of lower heat from LEDs have various cost benefits due to environmental control. The first step in quantifying savings relates to both the immediate energy reductions and the dynamics of by-product heat.

The Pros and Cons of By-Product Heat

Growers initially used HPS lamps in their greenhouses as supplemental lighting since that was the only viable solution before LEDs. The HPS spectrum contains a massive amount of infrared radiation, since it was developed for human eyes rather than for plants. Unfortunately, most PAR charts neglect to show the entire spectrum of HPS because they register only the photosynthetically active radiation, meaning a majority of PAR charts omit a majority of the radiation emitted by HPS lamps. Figure 1 below demonstrates the full HPS spectrum. (Figure 1).

LEDs create non-radiant (convective) heat that warms the air above the fixture rather than radiating it downward to plant surfaces. In contrast, HPS applies heat directly to the crop's leaves, making the crops warmer relative to the ambient temperature. Thus, switching to LEDs — or implementing a hybrid LED/HPS lighting plan — will necessitate an increase in air temperature. Increasing the air temperature enables the production gains possible with LEDs (as explained below); yet, it also increases heating costs. Ultimately, LEDs lower overall energy use by 10-25%.[1]

[Figure 1] THE HIDDEN INFRARED SPECTRUM OF HPS

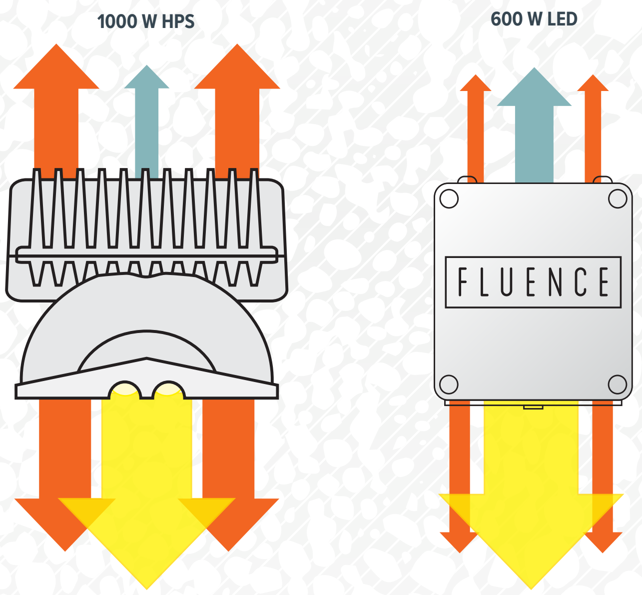


[1] Katzin, D., et al. Energy savings in greenhouses by transition from high-pressure sodium to LED lighting. Applied Energy. 2021.

Accounting for the High Costs of Thermal Waste

Operating a profitable greenhouse business is all about maximizing efficiency and reducing waste. One way to accomplish these goals is to decouple lighting from heating. In simplest terms, the electricity used to power HPS and LED lights in a greenhouse is converted to heat and light, then plants capture the photonic energy to transform CO_2 into useable biomass through photosynthesis. LED technology is simply more efficient throughout this conversion process and allows for better environmental control.

[Figure 2]



Irradiant heat/light balance depends on efficacy of HPS

Upper/lower balance depends on efficacy of LED

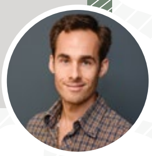
Decoupling heating from lighting by utilizing two dedicated systems (LED lighting and HVAC heating) offers greater environmental control than legacy HPS systems, reduces thermal waste, and minimizes cost. LEDs allow farmers to keep a more optimized and consistent growing environment, which improves both crop yields and quality. For example, in the warm season when ambient light is low and temperatures are already high, an HPS grower cannot add more light without overheating the crops. In response, HPS systems often require venting cycles, wasting precious CO_2 and creating a suboptimal and inconsistent growing environment with wild swings in temperature and humidity. This highly variable environment is stressful for plants and wasteful for growers. But, with LEDs, farmers have cooler supplemental lighting options that can counter these conditions and establish a consistent environment year-round. Compared to a stand-alone heating system, it is often 2-5x the cost to heat a greenhouse with lights (such as HPS) on a $/BTU basis.

Fluence VYPR fixtures employ a patented, passively cooled thermal management technology that does not rely on moving parts. Instead, its vertical heat sink conducts heat upward, away from the circuit board and away from plants. Due to the large surface area of the heat sink, the VYPR can operate in ambient temperatures as high as 40 °C.

For an HPS-to-LED retrofit, a simple comparison of fixture wattage can help to estimate cost savings. For instance, if PAR output is assumed to be equal, replacing a 1,000-Watt HPS fixture with a 600-Watt LED fixture reduces by-product heat by 40% without sacrificing total lighting efficiency. For a more nuanced and complex calculation that accounts for your legacy system and specific grow space, Fluence experts stand ready to calculate, design and implement a personalized lighting solution.

"If we calculate the cost of heating the greenhouse with energy from lighting and compare it to the cost of providing that heat from a dedicated heating system, we find in almost every case it is more cost effect to use a purpose-built heating system. I've never seen a case where heating from light is more cost effective than heating from a boiler..."

— Michael Hanan,
Fluence Commercial Agriculture Sales Manager



Quantifying the Total Energy Reduction of LEDs

A landmark study at Wageningen University & Research (WUR) in the Netherlands recently analyzed how transitioning from HPS to LED lighting saves energy in a wide variety of climates.[1] The heating and lighting needs of greenhouses depend greatly on location and climate — as does the return on an investment in LEDs. So, WUR's researchers used sophisticated modeling and climate data to predict energy-usage changes in a hypothetical tomato greenhouse at 15 diverse climates from subtropical to arctic.

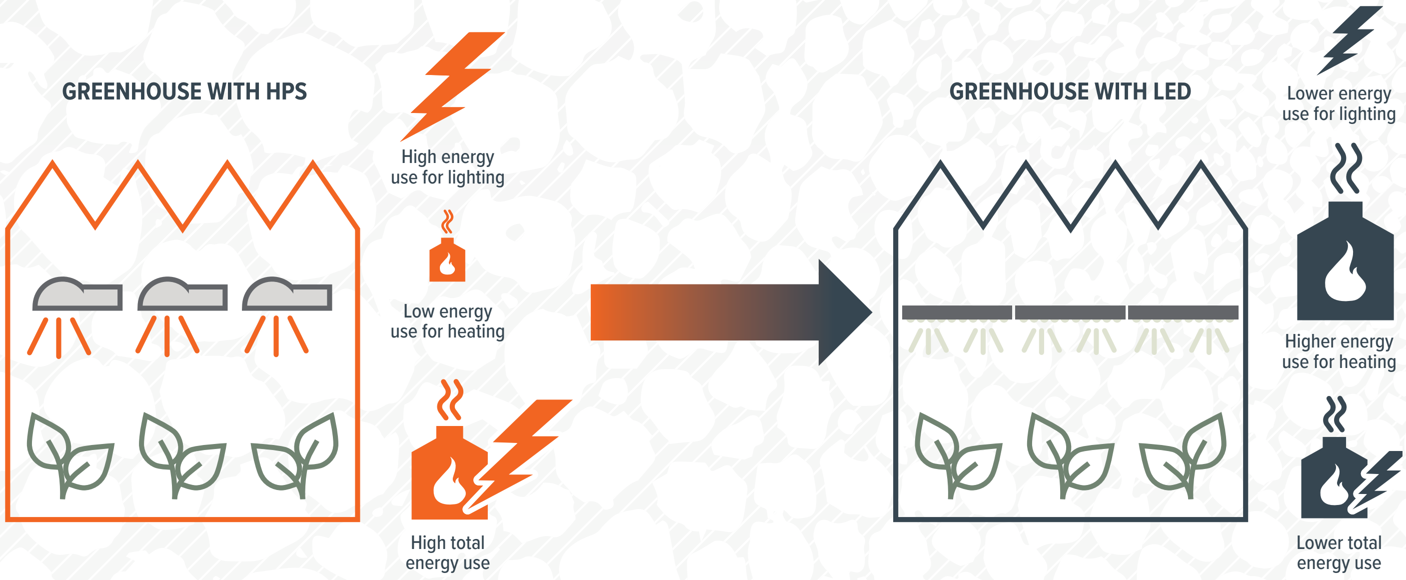
The study assessed energy vectors related to solar radiation, air temperature, relative humidity, horizontal radiation from the sky, insulation, ventilation, photosynthetic photon flux density (PPFD), and a variety of fixture efficiencies for both LEDs and HPS. LEDs' reductions in lighting energy were offset by increases in heating energy substantially, registering a 10-25% reduction in overall energy usage across all locations.

LEDs reduced lighting energy use by 40% and overall greenhouse energy use by 10-25%

A reduction in energy use does not equal a proportionate reduction in expenses; LEDs have a greater financial benefit when the prices of electricity and heat sources are factored. Inexpensive heat sources (e.g., geothermal, combined heat and power) will benefit the adoption of LEDs, while inexpensive electricity favors HPS. Whereas electricity is more expensive in most locales, LEDs effectively shift the utility load away from electric heating towards less expensive thermal energy sources.

[Figure 3]

THE HIDDEN INFRARED SPECTRUM OF HPS



Enhancing Environmental Control for Crop Quality & Yield

Though cultivators usually choose LEDs for their lower operating costs, the true benefit of LEDs is their increased production due to providing the proper wavelengths of light that plants prefer in addition to better environmental control and a higher PPF per joule.

VPD Management Made Easy

When HPS lights power down, several changes occur in the environment. As the ambient temperature decreases, the relative humidity (RH) increases, and in turn the vapor pressure deficit (VPD) decreases. Moreover, leaves that were heated by infrared cool more rapidly when heat is removed, leaving them vulnerable to condensation and pathogens.

With LEDs, diurnal and nocturnal temperatures are less dependent on lighting — as is humidity. Plants grown under LEDs transpire less than plants grown at the same PPFD. Less transpiration reduces facility water use, minimizes condensation on the greenhouse, and limits the need for dehumidification venting. Ultimately, lower lighting energy — at similar PAR values — translates to less heat and transpiration in the greenhouse and more control of the environment.

What Changes with LEDs

Maintaining optimal ambient temperature is critical for physiological functioning and pollen development in crops such as cucumbers and tomatoes. Without adequate heat, these crops slow their growth. Lower temperature is a concern when retrofitting a greenhouse with LEDs because the IR from the HPS lamps is no longer available. To compensate, cultivators need to increase the temperature setpoint in their environmental controls systems.

Trials conducted by WUR, Fluence, and Vortus Greenhouse Consultants found that that when using LEDs, increasing ambient temperature by 1.0 °C not only maintains crop production for tomato cultivars but also increases it — while further lowering overall energy costs compared to HPS. These trials are discussed further below.

The optimal temperature of an LED greenhouse is 1.0-1.5°C higher than that of an HPS greenhouse. Heat should always be managed through proper HVAC systems rather than the light source.

During warmer months, the lower IR heat of LEDs is an advantage because it enables lighting use when HPS lighting would be impossible due to excessive heating. Although heating costs may increase during colder months, these costs are off-set by uninterrupted crop production as a result of a more stable environment. Some facilities will need to modify their heating systems to implement LEDs, either by increasing the size of boilers or rerouting heat pipes. Most greenhouses can simply reprogram their environmental controllers. However, if any retrofit or hybrid integration increases total wattage, cultivators should expect heating loads to decrease.

Less Ventilation for Stable CO_2

Suboptimal CO_2 levels can be the limiting parameter in an otherwise optimal greenhouse. Especially as PPFD increases, CO_2 supplementation will be needed to obtain maximum gains. Crops prefer concentrations of 800-1,000 ppm, which promote earlier flowering and better fruit yield.

Yet supplemental CO_2 goes to waste if greenhouse venting is used for dehumidification or cooling when deploying HPS lighting. Venting events also cause swings in temperature as colder or warmer air enters the greenhouse. Limiting venting and maintaining steady climate control preserves CO_2, thus increasing photosynthesis, improving morphology, and lowering disease occurrence. Furthermore, to comply with light pollution regulations, many cultivators must use ceiling curtains that may limit ventilation and may present a fire hazard. Low-heat LEDs mitigate this risk and also limit the chance of plants overheating in the presence of curtains. Additionally, LEDs may reduce insurance premiums based on the lower risk of fire.

Lighting Strategy: Matching Wattage for Higher PPFD

In the greenhouse of yesteryear, HPS lights supplemented crops to 200-250 μmol/m²/s. This is mainly because of the limitation of the electrical infrastructure of the greenhouse and the heat that will be emitted if the growers targeted higher micromoles. The crops can be steered with higher light intensities and corresponding environmental adjustments. But with the advancement of LED technology, researchers are understanding that the saturation point of select crops is higher than once thought.

A 1% rise in PPFD typically yields a 1% gain in crop weight.

Cultivators today are following the lead of recent research and increasing PPFD to as high as 300 μmol/m²/s, depending on the cultivar. When a facility replaces an HPS system with an LED system of similar wattage, supplementation capacity nearly doubles, assuming efficacies of 1.8 μmol/J for HPS and 3.5 μmol/J for LEDs. Not only does the change increase daily light intake, but it also increases annual light intake in greater proportion because of the operating dynamics of LEDs.

Rethinking Daily Light Integral

Illuminating crops today ensures their salability tomorrow. And while controlled agriculture naturally provides more predictability than field agriculture, greenhouses struggle to overcome day-to-day and week-to-week fluctuations. First, because PPFD correlates so strongly with growth, several days of sub-optimal PPFD can upset production schedules. And, second, because controlling daily light integral (DLI) — the amount of PAR per square meter during the photoperiod is critical.

Retrofitting a greenhouse with LEDs improves DLI management in two important ways. First, because of the technology's lower by-product heat, LEDs extend supplemental lighting use into spring and fall for year-round production gains. And, second, because Fluence LEDs have variable output control, they enable daylight harvesting for more consistent PPFD levels on a moment-to-moment basis, as well as further electricity savings. Not all brands of LEDs are capable of dimming; always reference the product specifications before purchase.

Designing for DLI

Cultivators have an intuitive understanding of their DLI throughout the year. However, when making changes to supplemental lighting, calculations trump instincts. Greenhouse DLI is affected by:

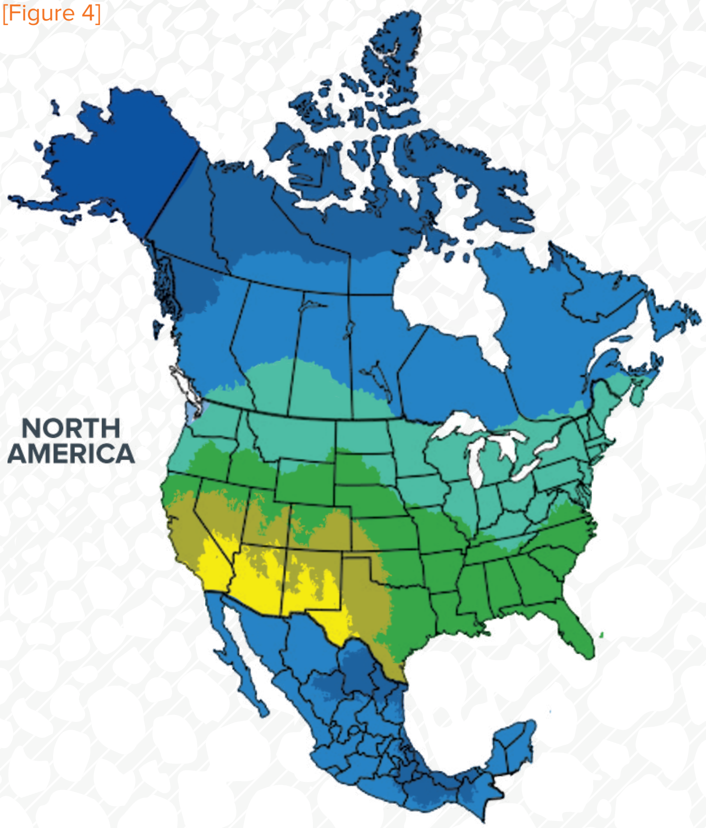
- **Latitude:** Facilities near the Arctic Circle will experience radical DLI seasonality that equatorial locations do not.
- **Climate:** Seasonal weather patterns influence DLI independent of daylength, as do altitude and coastal proximity.
- **Greenhouse features:** Coverings limit light transmission to 60-65% of the natural light depending on anti-reflective coatings and haze treatments. Infrastructure also obstructs light (e.g., trusses, light fixtures).

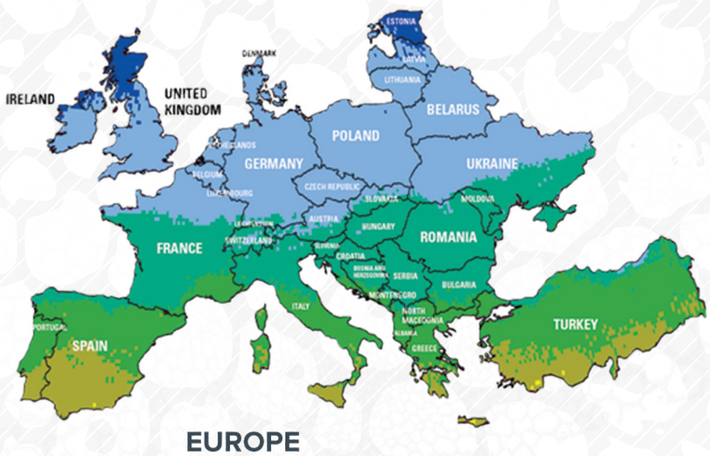
Thanks to climatologists, DLI maps are now available for every growing region worldwide. In some areas, outside DLI can top 65 mols; in others, such as the United Kingdom, average DLI is as low as 15 mols. By applying these maps in the system design process, lighting engineers can more precisely equalize month-to-month DLI — and regulate production.

The Fluence design team goes beyond simplistic mapping by using modeling software that predicts the day-to-day light conditions based on historic weather patterns. The power of a larger data set enables Fluence to predict the likelihood of anomalies and variations from average conditions. These capabilities enable a more confident system design, particularly in the face of climate change.

> ***"Sunlight may still be suboptimal during the warmer seasons. But with low-heat LEDs from Fluence, cultivators can run their lighting systems into the late spring for production gains that weren't possible with HPS."***

[Figure 4]



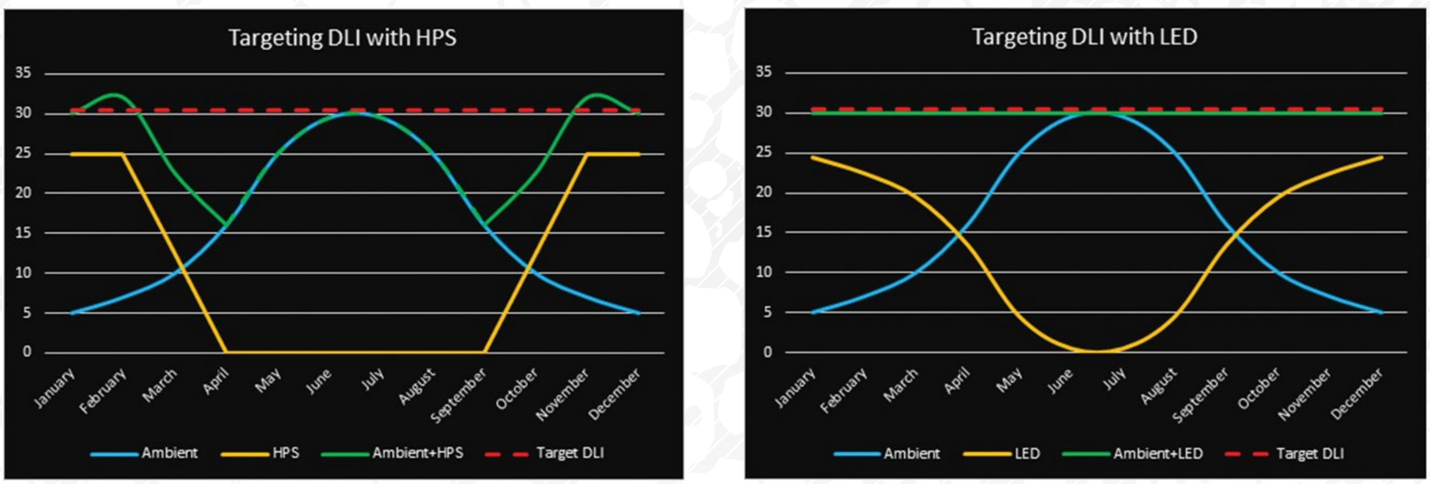


$$\text{DLI (mols/m}^2\text{)} = \frac{\text{PPFD (X } \mu\text{mol/m}^2\text{/s)} \times \text{60 Minutes/Hour} \times \text{60 Seconds/Minute} \times \text{Photoperiod (Hours)}}{1{,}000{,}000}$$

Choosing a lighting system entails more than a consideration of seasonal DLI. Horticulturists must consider crop requirements, production goals, and operating costs as compared to the capital expenditure of the system. Moreover, they need to assess the spectrum of the supplemental lighting and natural light, as discussed below.

LED greenhouses discontinue heating— not lighting — in late spring. Wherefore light is largely decoupled from heat, and because LED-lit crops prefer a higher ambient air temperature, light supplementation can continue into summer — or throughout summer — in many locations, further increasing plant production and consistency. In the WUR study noted previously, the

[Figure 5]



How LEDs Increase Year-Round DLI

A typical HPS strategy for managing DLI involves increasing light intensity in the winter months and often discontinuing supplementation as days lengthen in the late spring, due to the heat of the light fixtures. Then, until fall, the HPS lights go unused with perhaps the exception of some cool, cloudy days.

HPS lighting supplements DLI when PPFD is critically low. The objective is to lessen the extremity of the annual DLI bell curve (Figure 5) by increasing PPFD. **With LEDs, cultivators can completely flatten the DLI bell curve in many situations by providing light into the spring and summer at levels approaching the saturation threshold of the plant.**

hypothetical greenhouse was assessed based on climate data from Amsterdam (52.3676° N, 4.9041° E). When researchers modeled HPS use in the summer months, the greenhouse could not maintain the daytime setpoint (19.5 °C), and required significantly more ventilation than the LED greenhouse. As a result, CO_2 injection could not maintain the 1,000 ppm CO_2 setpoint at the same PPFD. Thus, as springtime temperatures and ventilation events increase with HPS, the economics of DLI management falter.

LED greenhouses discontinue heating — not lighting —in late spring

Daylight Harvesting Lowers Costs

Providing light in excess of a crop's saturation threshold is wasteful and potentially damaging. Photobleaching of chlorophyll compromises the photosynthetic ability of plants when appropriate light levels return. Moreover, supplementation beyond the saturation threshold diminishes financial returns. Daylight harvesting — the practice of using daylight to offset electrical lighting loads — precisely meets PPFD setpoints without the waste.

While dimming the lights may seem antithetical to the purpose of installing a high-PPF system, economic analysis reveals tangible benefits to this process. When cultivators couple their LED system controller with a PAR meter, they can dim their lights to maintain optimal moment-to-moment light levels and precise DLI. This saves on electrical costs and extends the life of the fixtures.

HPS lights cannot modulate their PPF. Of course, they can cycle power in response to weather, but excessive cycling leads both to reduced output and service life of bulbs. The opposite is true of LEDs; daylight harvesting increases their already-long lifespan.

Lighting Strategy: HPS/LED Hybrid Systems

Discarding a functional HPS lighting system may not be an economical choice, regardless of its operating expenses. Some cultivators create hybrid lighting systems by replacing some — rather than all — of their legacy HPS fixtures. Others add LEDs to their old systems and continue using their HPS fixtures to the maximum limit of their electrical capacity. Below are the benefits and limitations of a hybrid lighting strategy and design.

Incremental Changes with Hybrid Lighting

A hybrid system achieves several objectives. Most notably, a partial LED integration reduces up-front costs. Replacing every other HPS lamp with an LED fixture of equivalent photosynthetic photon flux (PPF) capacity circumvents electrical renovations, and rewiring is not necessary.

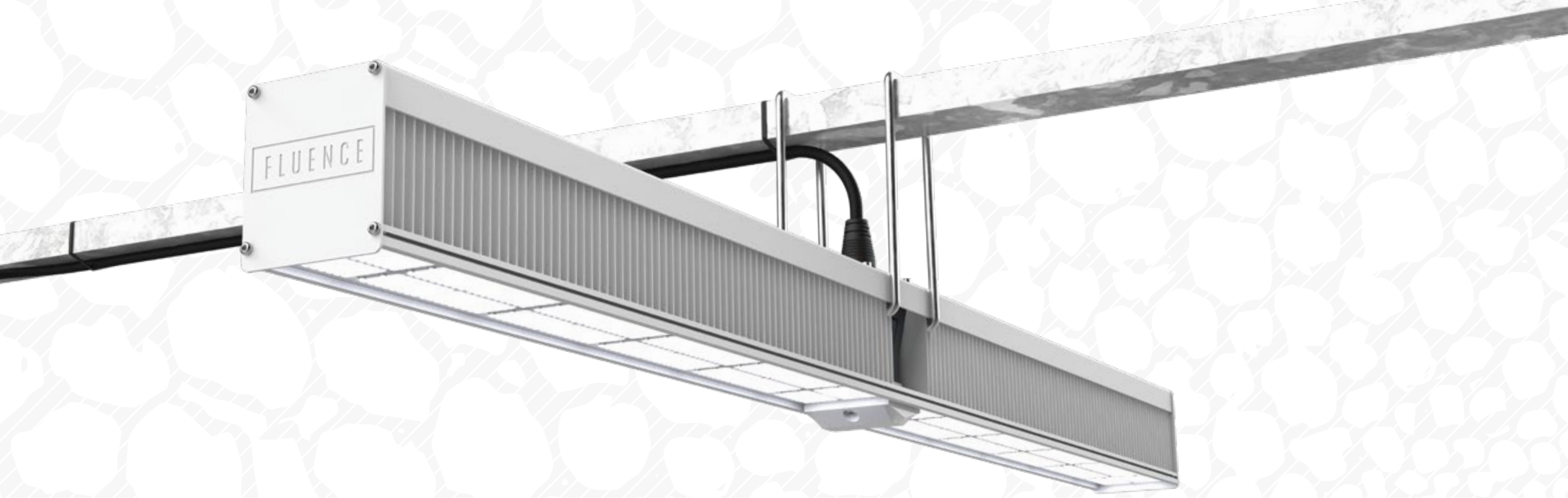
Adjusting Heat

Hybrid systems can leverage some of the low-heat benefits of LEDs while avoiding potential drawbacks. In the warmer months, cultivators may discontinue their HPS supplement and continue running only the LEDs into the summer at lower temperatures. A full LED retrofit may require supplemental heating sources in the winter months, depending on location. In those applications, transitioning only 50% of the light system to LEDs preserves the by-product heat of HPS and avoids costly renovations.

Managing Spectrum

Spectrum control is another reason for a hybrid integration. Many cultivators desire particular wavelengths of light that their HPS systems cannot adequately provide — such as blue light — or that their regional sunlight lacks during winter months. LEDs with a strong blue profile can induce compact growth when added to HPS. Red light may also be desirable for cultivators who wish to increase fruiting.

A narrow band LED with strong blue and red light is an energy efficient way to supplement HPS fixtures. If cultivators are replacing some HPS fixtures with LEDs, narrow band fixtures may be a favorable choice. Anticipating future changes to the light systems — such as an all-LED configuration — remains important to consider. In such a case, a narrow band of red and blue spectrum would not be recommended since LEDs would no longer be supplemental in application.



LED manufacturers that sell only narrow band fixtures will naturally recommend them for all applications. And for some greenhouses, a narrow band fixture (such as the Fluence VYPR DUAL) may indeed be best.

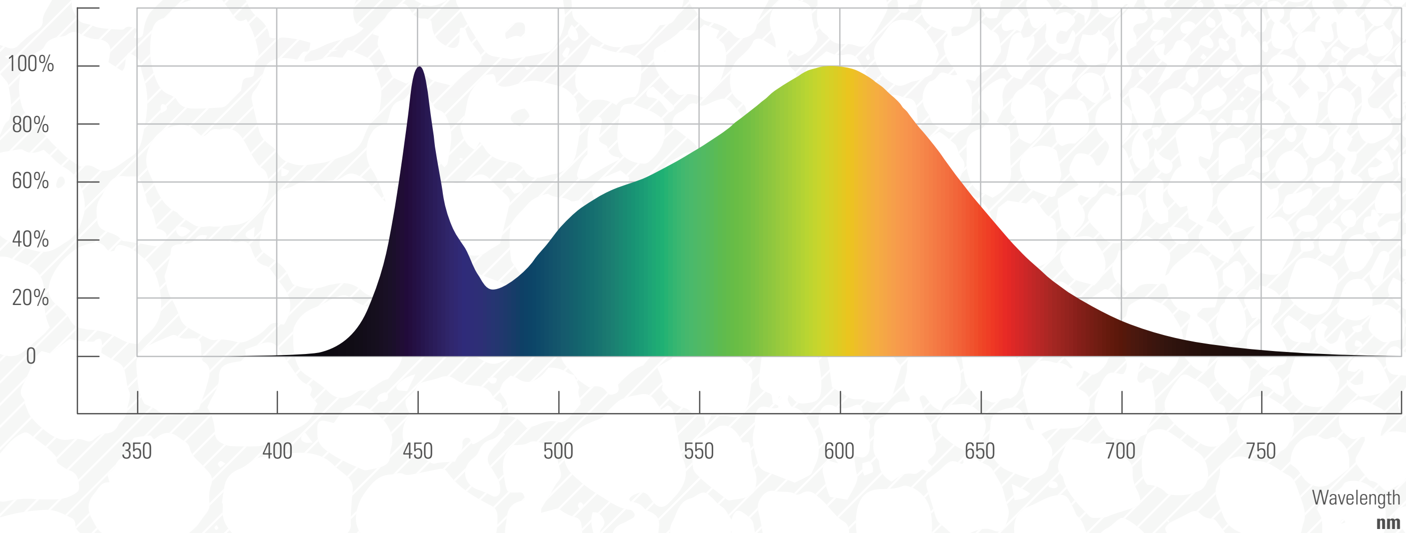
But if natural light levels are low during the winter, narrow band spectra can neglect important middle wavelengths that are not provided by the low proportion of natural light. In these instances, cultivators should work with Fluence to determine if a narrow band installation is appropriate. A more moderate spectrum usually yields better results in low-light conditions.

Choosing an LED Spectrum and Fixture

Unlike HPS lamps, which are restricted in their spectral output, LEDs can emit a variety of wave bands depending on their design. Fluence offers a number of choices on the VYPR top light platform with a range of spectra offerings, from broad white light to narrow band (Figure 6). While there is no ideal or "magic" spectrum, the versatility of LEDs enables cultivators and researchers to target precisely and deliberately the desired photoreceptors and pigments. The result is enhanced control of morphology, flowering, and other characteristics.

[Figure 6]

Measurements of Normalized Photosynthetic Photon Flux



Physics Meets Photobiology

An LED is a pairing of semiconductors that emits light when a voltage is applied. As electrons migrate from one material to another, they lose energy and release it as light. The color of light emitted — and the amount of power consumed — depend on the electrical properties of the two materials. Some colors of LED are electrically more efficient than others, but not all crops respond equally to all spectra.

Broad Spectrum LEDs

Broad spectrum light is best for most crops. The common misconception that plants do not use middle-spectrum light (i.e., green light), is just that — a misconception. In fact, for plants under strong white light, green can drive photosynthesis more efficiently than additional red.[2]

So-called "white" LEDs contain a variety of wave bands that include green and amber light. Often, a white LED is actually a blue LED coated with yellow phosphor to modify the spectra. These LEDs are less efficient than blue or red LEDs but more efficient than dedicated green LEDs. By including them in a fixture, engineers access the middle spectrum at the lowest possible electrical consumption.

Red and Blue LEDs

Blue and red wave bands are critical to plants because the two primary chlorophyll — chlorophyll a and b — absorb blue (400-499nm) and red (600-699nm) especially well. Incidentally, blue and red LEDs are among the most electrically efficient, making them a favorable choice for high-efficiency, narrow band fixtures.

A narrow band or mono band supplement, such as the Fluence DUAL R9B, can be efficacious for achieving specific photoresponses. And because narrow band fixtures produce more μmol/J than broad spectrum fixtures, they are an excellent choice for locations with sufficient natural sunlight. However, in the absence of year-round broad spectrum light, a heavily polarized spectrum may compromise morphology, flowering, and ultimately, product quality.

Lighting Ergonomics

The human eye is well-adapted for green light and struggles with narrow band blue/red light, particularly when it is applied in the absence of natural light. The poor ergonomics of narrow band lighting may impact one's ability to scout for pests or assess ripeness for harvesting due to color distortion.

Furthermore, beneficial insects evolved to work in natural light as opposed to narrow bands. Without blue and green light, bumblebees struggle to navigate their surroundings and are less effective as pollinators. Predatory insects, such as some parasitic wasps, are more mobile in the presence of green, blue, and ultraviolet light. However, under red light, these natural predators are less likely to walk or fly.

[2] Terashima, I. et al. Green Light Drives Leaf Photosynthesis More Efficiently than Red Light in Strong White Light: Revisiting the Enigmatic Question of Why Leaves are Green. Plant and Cell Physiology. 2009.

Selecting the Right Fixture

The best-suited lighting spectrum for a given application is a balance related to crop requirements, natural light, energy prices, and other factors. In turn, Fluence offers fixtures with a variety of spectra.

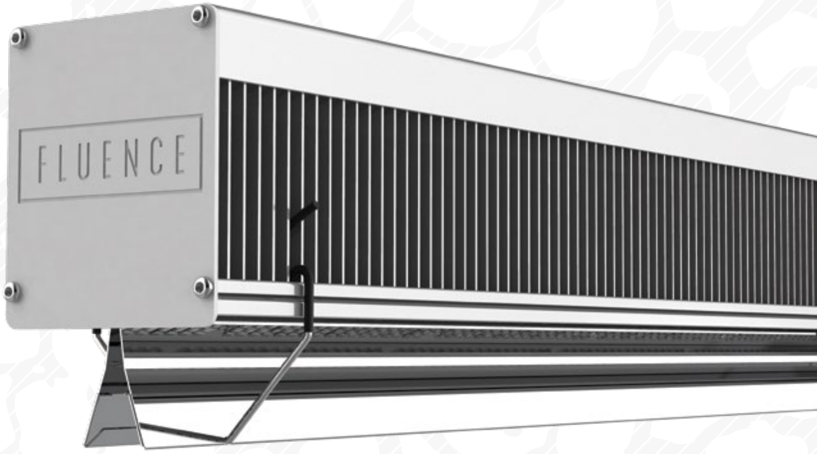
Thanks to the complexity of nature, there is no single-solution spectrum that works best for all crops and all goals. The grower's objectives for a particular crop are paramount, and the best spectrum may be different for cultivators seeking yield as opposed to those seeking specific quality attributes.

DLI and Narrow Band Spectra

Spectrum selection varies by crop and even by cultivar. Depending on the crop and location, cultivators may benefit from a narrow band spectrum — either a blue/red spectrum such as the Fluence PhysioSpec™ DUAL Spectra or a single-wavelength mono-spectra. These targeted spectra can reconcile the crop's needs to the available natural light or elicit specific photoresponses and morphology.

A narrow band fixture that maximizes PPF may not be the best choice for regions with low DLI during the winter season. If natural light intensity is not adequate, the isolated spectra of a narrow band fixture may cause undesirable morphology or suboptimal growth. As the days lengthen in the spring, and as natural light increases, a narrow band supplement makes up a smaller percentage of the overall DLI. The spectrum effectively shifts, and crops may respond poorly to the change. A broad spectrum light, such as the Fluence PhysiocSpec BROAD Spectra, is likely a better choice in low-DLI regions, despite its lower electrical efficiency.

We understand that high electricity costs may influence the choice of lighting spectrum. A narrow band spectrum may not be ideal for the crop, but if the PPF output is significantly higher than the broad spectrum alternative, it could be the best choice. Other considerations when selecting a spectrum are any future changes to the crop type or cultivar. A spectrum precisely adjusted to one crop will not necessarily suit others.



Maximum Light Distribution

As a greenhouse transitions to LED fixtures, PPFD levels often increase, raising important questions about how to uniformly distribute the added PAR — or simply mimic the HPS distribution pattern. A good starting point is an understanding of the legacy system's photosynthetic photon intensity distribution (PPID). A lighting consultant or a Fluence lighting designer can assess current distribution depending on the elevation of the lights, their placement, and their actual output.

Depending on your facility design, some LED light plans will struggle to achieve uniform distribution if placed in the same locations as the HPS fixtures because of the more direct angles of LED technology's light beams. In these select cases, and in order to meet PPID requirements, the Fluence VYPR fixtures feature a reflective adapter to properly distribute light at a lower level over the canopy. Using an optional reflector widens the coverage area. To further modulate distribution, the VYPR's mounting hardware is available in six configurations.

LEDs open up new possibilities for greenhouses with low ceiling heights, particularly when paired with a reflector that widens the PPID. Before the advent of LED technology, supplemental lighting was impossible with HPS lamps because of their high IR output. Now, with LEDs, lower-height facilities can increase light levels without burning the growing head of high-wire crops.

Moreover, lighting fixtures should minimize the obstruction of natural light. HPS lamps require a reflector due to the omnidirectional nature of their light emission, but LEDs present new form factors that complement greenhouse infrastructure. With LEDs, instead of an obstructive reflector, lights and power supplies can fit neatly under trusses to prevent the loss of natural light.

Superior Fixture Cooling

The diodes of an LED fixture create heat at their junctions to the printed circuit board. The heat compromises the output and longevity of the LEDs if not quickly dissipated. There are a few LED manufacturers who offer active cooling systems to manage heat. These designs either circulate a liquid coolant through the fixture or utilize an electric fan to circulate air across a heat sink.

Unfortunately, active cooling systems reduce the overall photon efficacy of the fixture because the cooling fan or pump consumes power. But more critically, active systems introduce points of failure to the design. When a fan malfunctions, a fixture can rapidly overheat and catastrophically fail. In damp or dirty environments — such as cultivation areas — moving parts are especially vulnerable.

Fluence VYPR fixtures employ a patented, passively cooled thermal management technology that does not rely on moving parts. Instead, its vertical heat sink conducts heat upward, away from the circuit board and away from plants. Due to the large surface area of the heat sink, the VYPR can operate in ambient temperatures as high as 40 °C without reliability concerns.

Assuring Fixture Quality

Not all LED fixtures are created equally in terms of reliability, longevity, or performance. Inexpensive products may promise high output and efficiency but fail to meet their specifications when installed. Some startup LED manufacturers back their fixtures with warranties that, while impressive, exceed the length of their company's existence.

Fortunately, selecting a reliable LED fixture is easier than ever. The DesignLights Consortium® (DLC) is a nonprofit organization that sets quality specifications for energy efficient lights, and tests lights to ensure accurate PPE, PPF, PPID and spectrum. The DLC also simulates extended usage to estimate the PPF capacity after extended operation.

Fixtures that maintain 90% of their initial output after 36,000 operating hours (Q_{90} ≥36,000) and accurately perform to their specifications are included in the DLC Qualified Products List (QPL). When lighting designers select a product from QPL, they are assured a reliable fixture that meets their design criteria.

To confirm that an LED fixture is listed with the Design Lights Consortium, please search the DLC Qualified Products List.

Fluence has more products listed with the DLC than any other lighting manufacturer. This helps cultivators easily qualify for rebates and incentives because many utilities reference the DLC QPL when assessing eligibility. Reference the section below to learn more about leveraging local rebates to lower your capital expenses.

Predicting Lighting ROI

How quickly LEDs pay back their purchase price — and how much additional profit they create over subsequent years — varies based on the location, crop, and facility. A Fluence lighting expert can help estimate the financial returns of an LED retrofit, which are often complex and unique to the application. However, an understanding of common considerations — and hidden operating expenses — can help lay the groundwork for planning.

Crop Value: Higher Revenue with LEDs

While overall energy use decreases by an average of 20% with LEDs, the most potent drivers of ROI are optimized quality and crop productivity. Crop weight is revenue, and increased revenue provides greater leverage than decreased costs.

[Table 1]

SPECIES, CULTIVAR: MERLICE, TOMAGINO		
	Compartment A	**Compartment B**
Temperature	**Day 21 °C** Night 16 °C	**Day 22 °C** Night 16 °C
Relative Humidity	57% ± 1.5%	57% ± 1.5%
[CO_2] Setpoint	1000 ppm	1000 ppm
Rooting Substrate	Rockwool	Rockwool
Fertigation Strategy	Standard Tomato Solution	Standard Tomato Solution
pH	5.5-6	5.5-6
EC	2.0-4.0	2.0-4.0
Supplemental Canopy Level | PPFD: 400-700nm	200μmol m^{-2} 2^{-1}	200μmol m^{-2} 2^{-1}

Fluence's study, supported by WUR and Vortus Greenhouse Consultants, documented these notable increases in crop weight. The trial — which intended to explore LEDs' ability to maintain yield rather than increase it — made a direct comparison of LED fixtures to HPS in a real-world commercial greenhouse.

Two tomato cultivars were selected (Merlice and Tomagino) and cultivated under standard commercial conditions using HPS and LEDs (Table 1). The LED treatment reduced energy use in both groups and increased the yield of the Tomagino group by 11% (when temperatures were increased by 1 °C). Thus, when calculating ROI, stakeholders can expect similar yield as compared to HPS — or even marked improvements. Vine length also decreased by 16% — a change that would reduce cultivation labor in a commercial setting.

LEDs increased tomato yield by 11% over HPS

When compared to HPS under the same conditions, research suggests that LEDs increase productivity due to their greater environmental stability. However, a host of other factors complicate yield predictions for the commercial cultivator. Cultivar, light spectra, and the previous lighting system influence gains along with the facility's environmental control capabilities and location.

The Fluence design team works with customers to assess all these variables, initially seeking to understand the greenhouse and the customer's goals. Our experienced horticultural engineers apply the latest research to select the most appropriate lighting system for the crop and application. Fluence can also analyze ROI with an assessment that includes energy prices, crop market prices, and the potential benefits to yield.

HPS and LED Maintenance

High-pressure sodium lights consume more electricity per photon. They also cost materials and labor due to relamping. Cultivators should annualize these expenses and factor them into their cost comparison of HPS to LEDs.

$$\left(\frac{\text{Lighting Hours}}{\text{Year}}\right)\left(\frac{\text{Bulb and Reflector Replacement}}{\text{X Hours}}\right) =$$

HPS lamp output degrades at a rate of 1% for every 1,000 hours of operation time. Some cultivators replace their bulbs regularly at intervals between 5,000 and 10,000 hours of operation; others suffer the reduced output of neglected maintenance. To that end, most HPS manufacturers recommend annual replacement of reflectors, which compromise the PPF of an HPS light by approximately 5% per year due to oxidation.

If fixtures run 16 hours per day and a bulb costs USD$55 (including labor), the annualized bulb maintenance cost is $36. A replacement reflector adds another $60. In total, an HPS fixture incurs $90-100 of maintenance per year. However, this figure does not include the lost production from maintenance downtime or light output degradation.

The expense of a neglected HPS system can easily exceed the cost of maintenance, as output can drop by 20% in a few years. When many cultivators measure their PPFD, they are surprised to find that their crop is not the same PPFD that it was designed for initially. It is important for the cultivators to measure their current light levels under the HPS to get an understanding of the decrease in PPFD from the original installation of HPS. For eg. if the original installation was for 220 micromoles/m²/sec after 3-5 years that same number might be at 170 micromoles/m²/sec

Electricity prices are a significant consideration in relamping intervals. If the local price is $0.06/kWh, relamping is less urgent than in regions with $0.30/kWh costs. In fact, extremely low electricity prices may negate the benefits of LED retrofitting entirely.

Lower Maintenance Costs

Fluence LEDs do not require regular maintenance. In the event that the diodes become fouled by pollen or dirt, the fixture can be turned off, allowed to cool, and sprayed with a solution of soap and water. Always confirm that an LED fixture is rated for wet locations before washing. The VYPR Series has an IP66 wet-location rating.

LEDs retain their output better than HPS lamps as they age, maintaining 90% output after 36,000 hours. The service life of an LED system is approximately 50,000 hours, — which is the approximate service life of a digital HPS ballast. Practicing daylight harvesting can further extend the fixture's life span, as lowering the operating current produces less heat. If cultivators attempt daylight harvesting with HPS fixtures — which cannot dim — the on-off cycling damages the electrode and shortens the service life.

Other LED Capital Expenditures

The installation costs of LEDs are not limited to their purchase price. Depending on the facility, the electrical infrastructure or heating system may require updates.

In many installations, LED fixtures can replace HPS without changes in wiring because they consume less power, even at higher PPF output. However, repositioning may be necessary if the LEDs distribute light differently than the HPS lamps. Likewise, if cultivators desire a large increase in lighting capacity, they will need to seek estimates for a renovation.

The efficiency of LEDs may necessitate an increase in heating capacity, though many facilities will simply increase their set point without mechanical changes. Some may plumb an additional tube to bring heat to the growing head of the plant, but doing so is not usually necessary. Combustion air heaters can be a suitable and modular solution to increased heating requirements, especially as they introduce CO_2 to the cultivation area.

Finding Financial Assistance

Due to their lower electrical consumption, LEDs reduce the environmental impact of conventional electricity production. They also place less strain on the electrical grid. These benefits have compelled both governmental and private organizations to incentivize LED adoption with financial assistance programs.

In the United States and Canada, utility companies incentivize energy efficiency to reduce the demand on their infrastructure. Promoting usage reduction is often more cost-effective than adding electrical production capacity, so utility companies regularly assist with 25-30% of capital expenses, and 50% or more in some cases.

> ***"As of spring 2021, the Fluence rebate program has saved customers over $15M on their LED fixtures. With our close collaboration with customers and their local utility providers, we are able to facilitate rebate applications to make the most of the local incentives. "***
>
> **— Brady Nemeth,**
> **Fluence Utility Rebate Coordinator**

How Fluence Helps Fund Your Project

- Confirms the availability of funding and your eligibility
- Works with utility representatives to establish expectations and meet deadlines
- Assists with analysis of energy reduction and documentation
- Attempts to negotiate custom incentives with utility companies if programs are not available

Typically, utility companies offer one of two types of programs based on either prescriptive rebates or custom incentives, though some employ a hybrid model. Prescriptive rebates pay a predetermined sum for the purchase of a qualified LED fixture to replace HPS. The approved fixtures are often based on the DLC Qualified Product List. Custom incentive programs, by contrast, require an assessment of the cultivator's current energy use and light system. The refunding is based on the savings in energy use (kWh), demand (kW), or some combination of the two.

In the European Union, the common agricultural policy (CAP) will expand environmental initiatives this coming decade to meet European Green Deal benchmarks. In the 2021-2027 period, CAP will create new streams of direct payments for "eco-schemes" — strategic plans to meet Green Deal targets. Cultivators can anticipate newly allocated funding that will be distributed through national and regional programs. Those planning an LED investment should start by contacting their local authorities for the latest opportunities.

Start the Process Early

Cultivators should contact Fluence early in their planning — even if the specifications of a retrofit design are likely to change. Annual funding from utility companies may be exhausted or may become exhausted before the project's completion.

Now is the Time for the Future

Just as HPS technology revolutionized greenhouse agriculture in the 20th century, LED technology is reforming and retrofitting the greenhouses of the 21st century. Lower operating costs are only one side of the equation; the other side boasts higher yields, quality, and marketability. Ultimately, LEDs empower cultivators with more control over spectra, environment, and PPFD, enabling them to grow smarter than ever before.

Fluence is dedicated to bringing cultivators the scientific evidence they need to make informed decisions on their LED lighting solutions. We work passionately with our growers from start to finish. Each retrofit installation begins with an analysis of the legacy light system in order to develop a customized lighting strategy that meets each grower's specific goals by the end.

Why Make the Switch to LEDs:

- Reduce lighting energy by 40% and overall energy by 20%.
- Enable better environmental control for enhanced quality and yield.
- Increase warm-month DLI for year-round production gains.

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