



Evaluating Supplemental Light for Your Greenhouse

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For greenhouse crops where increased photosynthesis leads to greater revenue (for example more turns of an impatiens plug crop or increased yield of cut flowers), supplemental lighting can be a profitable investment. In this article, we discuss seven aspects of supplemental lighting to help you select the best lighting strategy for your location and crop.

1. Understanding the jargon of light units

Light can be measured in several ways. When comparing one light system against another, and to interpret lighting recommendations from this and other sources, it is useful to understand how units relate to each other.

Table 1 compares units so that you can make conversions to units with which you are familiar. Our industry usually measures light in foot-candles. This measure of visible light (i.e. light visible to the human eye) does not exactly correspond to the spectrum of light energy used by plants in photosynthesis (which is the range of 400-700 nm wavelengths, termed “photosynthetically active radiation” or “PAR”).

Horticulture researchers usually measure instantaneous light level as the number of micromoles of photons in the PAR spectrum that reach one square meter each second ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), because this unit quantifies light energy used in photosynthesis. At noon in summer, outdoor sunlight reaches about $2000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (10,000 foot-candles). We can also quantify how much PAR light energy reaches a square meter during a full 24-hour period in units of moles of PAR light that reach one square meter over the course of a day ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, or, as we will describe it here, “moles/day”). If we think of instantaneous light level ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) as the number of drips of water (light) falling on one square meter each second, then daily light integral (in moles/day) would be a bucket holding the water (light energy) that has accumulated over the entire day.

2. Daily light integral increases crop yield

Greenhouse supplemental lighting for increased growth is typically in the range of $40\text{-}80 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (300-600 foot-candles) for 6-12 hours, using high-pressure sodium (HPS) or metal halide (MH) lamps. Lighting designs for photosynthesis (growth) require much higher light output than for photoperiod (day length and flowering) control of plants such as poinsettias and chrysanthemums. Photoperiod lighting only needs $2\text{-}4 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (10-20 foot-candles) and is usually delivered as a night break of four hours from 10 p.m. to 2 a.m. using strings of incandescent lights.

Most crops benefit from supplemental lighting, but the technology is only profitable when increased growth and quality can be converted into added revenue. The floricultural crops lit most often are plugs and cut flowers, because in these cases increased growth rate also corresponds to greater economic yield. Plug species including geranium, petunia, vinca, begonia, impatiens, lisianthus, and gerbera have a shorter production time under lighting (Styer and Koranski, 1997) and result in more compact, branched plants that flower earlier in the finished container. For cut flowers, the increased number of stems, and greater value per stem in terms of length and flower size provide extra revenue from lighting.

When light energy is added up over an entire day, there is an approximately straight-line relationship between daily light integral and yield. Figure 1 shows a graph of cutting production from *Scaevola* stock plants that received different amounts of light energy per day (all with an 11-hour photoperiod in order to keep plants vegetative). In this experiment in a glass greenhouse during Nov-Dec, ambient light was 6-7 moles/day and other light levels were provided with either shading or HPS supplemental lighting. Figure 1 also shows that response to light was greater when carbon dioxide was injected in the greenhouse.

3. How much sunlight reaches the crop?

In the northern U.S., daily light integral can range between 1-50 moles/day through the year depending on season and cloud cover. Research at Clemson University used 30 years of light data to calculate “light maps” that show the average daily light integral throughout the U.S. in different months of the year. These light maps can be downloaded from <http://virtual.clemson.edu/groups/hort/faculty/faust/maps.htm>.

Transmission of light into the greenhouse is usually in the range of 35 to 75%. In other words, if sunlight provides $1000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ outside the greenhouse, with a light transmission of 50% then only $500 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ would reach the greenhouse bench. In addition to considering investment in lighting, it is also important to consider ways to increase light transmission:

- covering type (for example, around 90% transmission for single glass versus 76% for double-poly, Nelson (1998)). These transmission rates do not include the factors listed below, for example the greenhouse structure, which further reduce light in the greenhouse. Light striking a greenhouse covering on an angle also usually has lower transmission than a light beam that directly strikes the glazing material.
- cleaning or replacing covering on a timely basis (dusty on glazing can reduce light by 20%)
- wide-pane, framing designed for minimal shading, or open roof structures (structure can easily reduce light by 15%)
- minimizing hanging baskets above crops
- reducing overhead “clutter” (e.g. conduit and piping)

Figure 2 shows the daily light integral at the greenhouse bench in Ohio each month, assuming 50% light transmission. Daily light integral in Ohio, *on average*, is similar to most other northern states. Assuming 50% transmission, daily light integral averages around 6 moles/day during November to January, and above 26 moles/day in mid-summer.

4. How much does supplemental lighting contribute relative to sunlight?

Table 1 shows how to convert from a specific number of foot-candles to daily light integral (moles/day) for different light sources:

- Multiply the number of foot-candles \times the hourly correction factor (from Table 1) \times the hours lit to get the moles/day.
- For example, HPS at 400 ft-c for 12 hours
 - $400 \times 0.00047 \times 12 = 2.3$ moles/day

Low sunlight increases the relative effect of supplemental lighting on total light level, and therefore on plant growth. Figure 2 shows the light contribution from sunlight alone, and also the total amount of light (another 2.3 moles/day) if HPS was run at 400 ft-c for 12 hours. During November to January, an extra 2.3 moles/day from HPS would provide about 37% more light compared with sunlight alone. In contrast, HPS would only provide 10% more light during June to August, the brightest months. Given that increased daily light integral can provide a corresponding increase in crop yield, the potential impact on growth and revenue is therefore greatest from November through January.

5. Obtain professional help to select the optimum system

Commercial light suppliers can provide a lighting design for HPS or MH for your greenhouse, along with a map which shows uniformity of light across the benches. Light uniformity is extremely important to ensure evenness of crop growth, height and flowering, and also to allow consistent watering across the greenhouse. Lamp designs are distinguished by their type of reflector. The style of reflector (wide or focused) determines the footprint of light provided. For example, a greenhouse with low side-walls generally requires a wider-spreading reflector than a greenhouse in which a high fixture height is possible.

For growers who purchased light fixtures years ago and do not know the light output or uniformity from their lamps, it is worthwhile to purchase a light meter, preferably with units in $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and measure light level from the lamps at night. Light uniformity can be measured several ways, but a rough guideline for acceptable uniformity is that the minimum light level (in the darkest spot) should be no less than 70% of the highest light level in the brightest spot (Aldrich and Bartok, 1994).

High-pressure sodium or metal halide lamps are used for supplemental lighting because these fixtures are efficient at converting electrical energy into PAR light (20-25%), and are also

available in high wattages (usually 400-1000W in greenhouses). High-pressure sodium (HPS) lights are much more common in greenhouses than metal halide, although both have similar efficiency in converting electrical energy to PAR (20-25%). HPS emits enough red light to provide an effect on daylength perception in plants (i.e. HPS can promote both growth and flowering in long-day plants including many annuals). Metal halide provides more blue light than the orange/yellow HPS, and because plant color is less distorted under MH these fixtures are used for displaying plants in retail settings.

To provide a desired light level, installing a small number of large fixtures is generally the lowest-cost system. If your greenhouse has low side walls or a low average light intensity is desired, however, light uniformity becomes more difficult with large fixtures. In this scenario, it is necessary to install a larger number of small-wattage fixtures.

Other options in lamp technology include the type of ballast, and reflector. Some companies produce remote ballasts that are connected to the reflector by an electrical cord, which means that the ballast can be located in a place that does not shade the crop and the weight and structure needed to support the fixture is greatly reduced. Ballasts are already available that can be changed from MH to HPS fixtures by changing the bulb and flicking a switch on the ballast. A new type of MH bulb (“HPIT-Plus”) produced by Phillips Lighting Co. can fit into both HPS and MH ballasts. Additionally, electronic ballasts are currently being tested for greenhouse use. Electronic ballasts could significantly reduce energy consumption (by around 50 or more Watts/lamp) and allow the lamp to be “dialed down” in intensity.

6. Calculate investment and operating costs

By calculating investment and operating costs for supplemental lighting, we can determine how much extra revenue is needed for a positive return on investment. Table 2 shows a break-down of investment costs for two light levels in a free-standing greenhouse. Note that investment costs would be lower for high-walled, gutter-connected houses where a more efficient lighting pattern can be established. For a complete financial analysis, it would be necessary to convert initial investment costs into an annual cost over the life of the fixtures (at least 15 years). Annual investment

cost adds about \$0.50 to \$0.73/square foot of floor space/year (350 or 575 ft-c, equal to 46 or 75 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) using the annuity method and typical accounting assumptions. If lights are run for 17 weeks per year (a typical duration of lighting in the northern U.S.) that would add \$0.03 to \$0.04 of investment cost per square foot/week during winter production.

There is a minor maintenance cost to clean the lamps each year and replace bulbs. Bulb life for HPS is around 16,000 hours or more, so they normally last several years.

There is also a heating benefit from the lamps, although electricity is always an expensive way to heat a greenhouse. Assuming that 75% of energy is useful for heating the greenhouse and results in heat fuel savings, and the greenhouse is heated with #2 fuel oil costing \$1.00/gallon then savings would be \$0.0008 (350 ft-c) or \$0.0013 (575 ft-c) per square foot/week for every hour per day that lights are run (for example, about \$0.01 per square foot/week if lights are run for 12 hours a day at 350 ft-c).

Operating costs are primarily electrical. Electrical costs per square foot per week for the two investment scenarios (350 or 575 ft-c HPS in a free-standing greenhouse) can be calculated using the following formula:

- Number of hours operated per day x \$/kW/Hour x 0.03 (350 ft-c), or
- Number of hours operated per day x \$/kW/Hour x 0.05 (575 ft-c)

For example, to run HPS at 350 ft-c for 12 hours per day at \$0.10/kW/Hour = 12 x \$0.10 x 0.03 = \$0.036 per square foot per week for electricity.

7. Use lights efficiently to minimize cost and maximize benefits

One way to reduce operating costs and maximize effectiveness of lighting is to only run the lights during hours and on days when ambient sunlight is low. Lighting during cloudy winter days or during the night adds the most photosynthesis per $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of HPS added. An efficient lighting strategy, using an environmental control computer, turns lights off when sunlight level is already high. For example, research with *Scaevola* stock plants found that photosynthesis rate begins to plateau when sunlight is above 400 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (2000 ft-c for sunlight), and this would be a suitable threshold level for turning off lights in that crop.

Be prepared to change other aspects of your production when adding lights. Figure 1 shows that as light level increased, supplemental carbon dioxide increased the effectiveness of lighting on cutting production (again more return per $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of light added). For the same reason, temperature is usually increased a few $^{\circ}\text{F}$ to maximize photosynthesis rate when adding supplemental lighting. Bill Swanekamp at Kube-Pak in NJ notes that adding lights to plug crops requires fine-tuning of nutrition, irrigation, and growth retardant applications because lit crops grow and dry out more quickly and tend to be more compact than crops grown under natural light. Scheduling is also affected, because not only does photosynthesis increase, but the extra radiant energy from supplemental lights can increase plant leaf temperature by up to 5°F (Styer and Koranski, 1997).

Run small-scale trials to evaluate which species and cultivars are more profitable under supplemental lighting. We found that HPS lighting of stock plants for specialty-annuals had a greater effect on cutting production for some cultivars than others. In our trials, where plants were lit during an 11-hour photoperiod at 46 or 75 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (350 or 575 ft-c) using HPS, the increased cutting production for Scaevola, Supertunia, Tapiens Verbena, and Lemon Verbena was profitable. For some other species, for example Heliotrope, Lantana, and New Guinea Impatiens the extra cuttings produced under lighting did not cover the operating and investment costs of HPS. If running a greenhouse trial, be sure to fine-tune other aspects of production (e.g. watering) so that you have a fair comparison in technologies.

Table 1. Conversion between different light units

Unit	Type of measurement	Mainly used by	Compared with 1 foot-candle		
			Sunlight	H.P. Sodium	M. Halide
Foot-candles	Visible (human eye)	Industry (U.S.)	1	1	1
Lux	Visible (human eye)	Industry (Europe)	10.76	10.76	10.76
$\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of PAR (400-700 nm)	Quanta of light in PAR range	Horticulture research	0.20	0.13	0.15
moles/day (PAR)	“daily light integral”: accumulated PAR light during an entire day	Horticulture research	foot-candles \times 0.00071 \times hours of light	foot-candles \times 0.00047 \times hours of light	foot-candles \times 0.00054 \times hours of light
Watts/ m^2 (PAR)	Energy in PAR range	Engineers, research	0.043	0.026	0.033
Watts/ m^2 (total energy)	Total energy	Engineers, research	0.101	0.074	0.089

Table 2. Example investment costs for high-pressure sodium lamps to provide 46 or 75 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (350 or 575 foot-candles) in a 30 ft. x 144 ft. double-poly free-standing greenhouse.

	46 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (350 foot-candles)	75 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (575 foot-candles)
Lamp design		
Number of 400W fixtures	40	66
kW/greenhouse (400W bulb + 64W ballast)	18.6	30.6
Square feet of floor space/lamp	108	65
Initial costs		
Purchase cost of fixtures @ \$210	\$8,400	\$13,860
Installation cost @ \$190 ^a	\$7,600	\$12,540
Total purchase and installation	\$16,000	\$26,400
Investment cost/square foot of greenhouse floor space	\$3.80	\$6.10

^aAssumes a permanent installation by a grower paid \$12.15/hour.

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Figure 1. Response in cutting number of Scaevola 'New Wonder' stock plants to different amounts of daily accumulated light energy, and under both ambient and supplemental carbon dioxide levels.

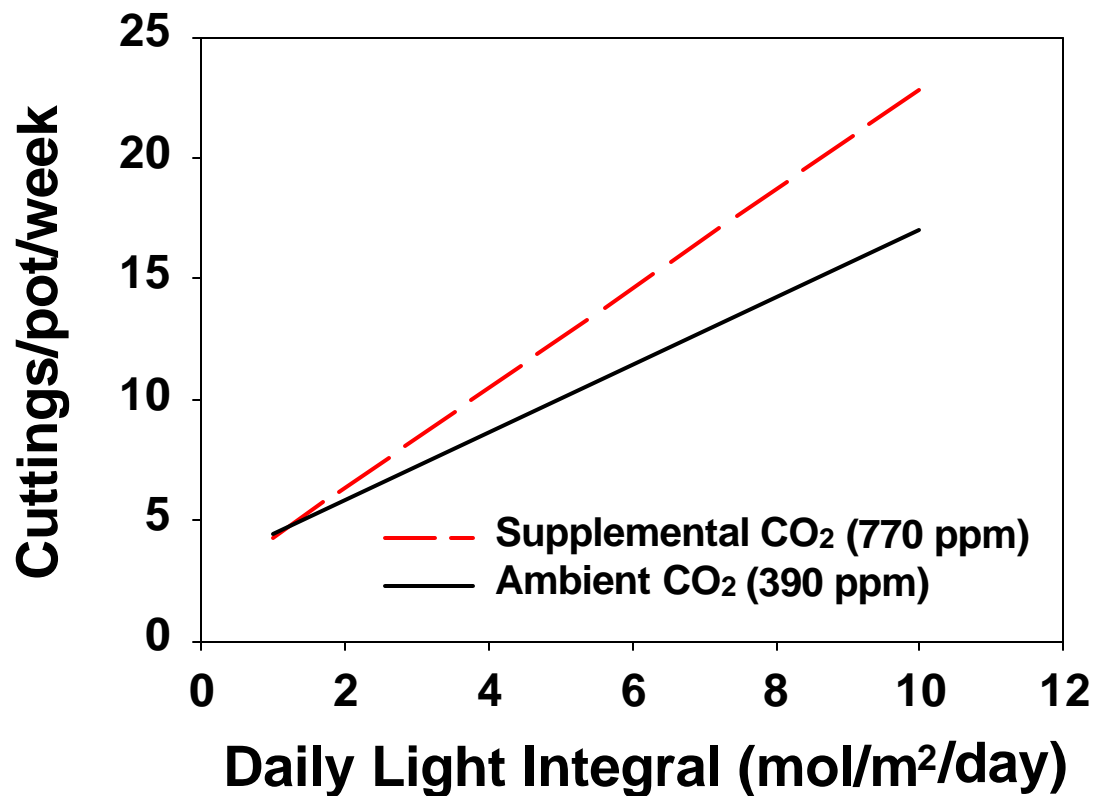


Figure 2. Daily light integral in Ohio received at the greenhouse bench level during different months of the year (solid line). The solid line assumes 50% light transmission, based on light maps developed at Clemson University. The dotted line represents sunlight plus an additional 2.3 moles/day contributed by HPS at 400 ft-c for 12 hours/day.

