Economic Analysis of Greenhouse Lighting:
Light Emitting Diodes vs. High Intensity Discharge Fixtures

Jacob A. Nelson and Bruce Bugbee

Crop Physiology Laboratory, Department of Plant Soils and Climate, Utah State University, Logan, UT 84322-4820 USA

This paper is complemented by a five-year cost calculator for plant lighting:
http://cpl.usu.edu/htm/publications/file=15575

Lighting technologies for plant growth are improving rapidly, providing numerous options for supplemental lighting in greenhouses. Here we report the photosynthetic (400-700 nm) photon efficiency and photon distribution pattern of two double-ended HPS fixtures, five mogul-base HPS fixtures, ten LED fixtures, three ceramic metal halide fixtures, and two fluorescent fixtures. The two most efficient LED and the two most efficient double-ended HPS fixtures had nearly identical efficiencies at 1.66 to 1.70 micromoles per joule. These four fixtures represent a dramatic improvement over the 1.02 micromoles per joule efficiency of the mogul-base HPS fixtures that are in common use. The best ceramic metal halide and fluorescent fixtures had efficiencies of 1.46 and 0.95 micromoles per joule, respectively. We also calculated the initial capital cost of fixtures *per photon delivered* and determined that LED fixtures cost five to ten times more than HPS fixtures. The five-year electric plus fixture cost per mole of photons is thus 2.3 times higher for LED fixtures. If widely spaced benches are a necessary part of a production system, the unique ability of LED fixtures to efficiently focus photons on specific areas can be used to improve the photon capture by plant canopies. Our analysis demonstrates, however, that the cost per photon delivered is higher in these systems, regardless of fixture category. The lowest lighting system costs are realized when an efficient fixture is coupled with effective canopy photon capture.

Acronyms: Light Emitting Diode (LED), High Pressure Sodium (HPS), Photosynthetic Photon Flux (PPF), Ceramic Metal Halide (CMH), High Intensity Discharge (HID)

Rapid advances in lighting technology and fixture efficiency provide an expanding number of options for supplemental lighting in greenhouses, including numerous LED fixtures (see [1,2] for a history of LED lighting in horticulture). Significant improvements have been made in all three high intensity discharge (HID, which includes HPS and CMH) fixture components: the lamp (often referred to as the bulb), the luminaire (often referred to as the reflector) and the ballast. High pressure sodium (HPS) fixtures with electronic ballasts and double-ended lamps are now 1.7 times more efficient than older mogul-base HPS fixtures.

Lighting technologies vary widely in how radiation is distributed (Fig. 1). There is no ideal pattern of radiation distribution for every application. In large greenhouses with small aisles and uniformly spaced plants, the broad, even output pattern typically emitted from HPS fixtures provides uniform light distribution and good capture of photosynthetic photons. In smaller greenhouses with spaced benches, the more focused pattern typically found in LED fixtures can maximize radiation transfer to plant leaves. As the area covered by plants increases, the need for focused radiation decreases (Fig. 2).

In greenhouse applications, selection among lighting options should primarily be made based on the cost to deliver photons to the plant canopy surface. This analysis includes two para meters: 1) the fundamental fixture efficiency, measured as micromoles of photosynthetic photons per joule of energy input, and 2) the canopy photosynthetic photon flux (PPF) capture efficiency, which is the fraction of photons transferred to the plant leaves.

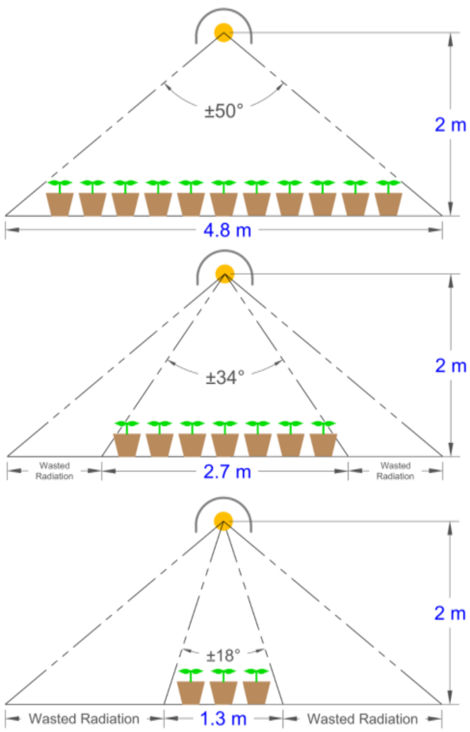

Figure 2 Canopy photon capture efficiency. As the plant growth area under the fixture gets smaller, wasted radiation often increases. Values are shown in meters, but this can be scaled as a unit-less ratio. Multiple overlapping fixtures are typically used to achieve uniform light distribution.

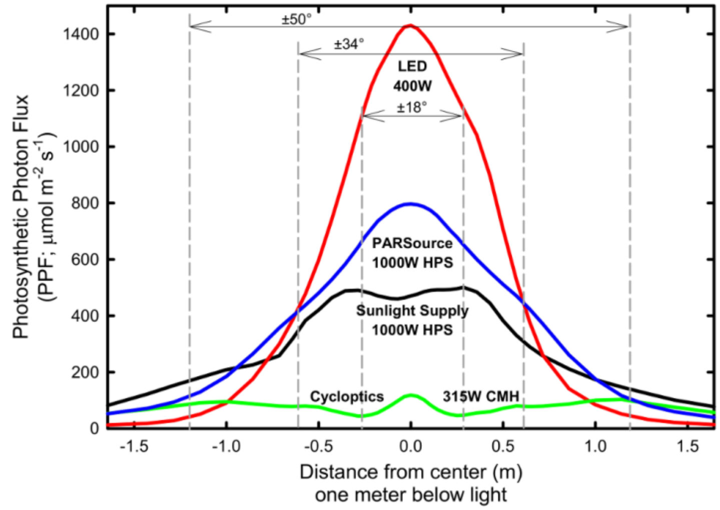

Figure 1 The light distribution of four fixtures with similar photon efficiency. The LED fixture (Lighting Sciences Group) uses optics to achieve a narrow distribution, with the majority of the photons falling in a concentrated pattern directly below the fixture. Conversely, the Cycloptics ceramic metal halide fixture is designed for even light distribution, and therefore casts uniform radiation over a large surface area. Since the area increases exponentially as the distance from the center increases, the photon flux farther from the center represents a larger quantity of total photons.

Photosynthetic efficiency is best measured as µmoles per Joule. The efficiency of lamps is often expressed using units for human light perception (lumens or foot-candles) or energy efficiency (watts in per watt out). Photosynthesis, however, is determined by moles of photons. It is thus important to compare lighting efficiency based on photon efficiency, with units of micromoles of photosynthetic photons per joule of energy input. This is especially important with LEDs where the most electrically efficient colors are in the deep red and blue wavelengths. A dramatic example of this is the comparison of red, blue, and cool white LEDs (Table 1). The low energy of red photons allows more photons to be made per unit energy (energy is inversely proportional to wavelength, Planck's Equation). Conversely, blue LEDs can have a 53% higher energy efficiency (49% vs. 32%) but only a 9% higher photon efficiency (1.87 vs. 1.72).

Table 1. Efficiency of individual LEDs at a drive current of 700 mA.

LED Color	Peak wavelength or color temperature	Photon efficiency[z] (µmol/J)	Electrical efficiency[y] (%)	Luminous efficiency[x] (lm/W)
Cool white	5650 Kelvin	1.52	33	111
Red	655 nm	1.72	32	47
Blue	455 nm	1.87	49	17

[z]-Photon efficiency is the most appropriate measure for photosynthesis.
[y]-The relationship between electrical efficiency and photon efficiency is dependent on wavelength (Plank's equation $E=hc/\lambda$).
[x]-Luminous efficiency is shown to demonstrate how inappropriate it is as an indicator of lighting efficiency for plants.

Effect of light quality. There is considerable misunderstanding over the effect of light quality on plant growth. Many claims have been made associating increased plant growth with light quality (spectral distribution or the ratio of the colors). A widely used estimate of the effect of light quality on photosynthesis comes from the Yield Photon Flux (YPF) curve, which indicates that orange and red photons between 600 to 630 nm can result in 20 to 30% more photosynthesis than blue or cyan photons between 400 and 540 nm (Fig. 3)[3,4]. When light quality is analyzed based on the YPF curve, HPS lamps are equal to or better than the best LED fixtures because they have a high photon output near 600 nm and a low output of blue, cyan, and green light [5].

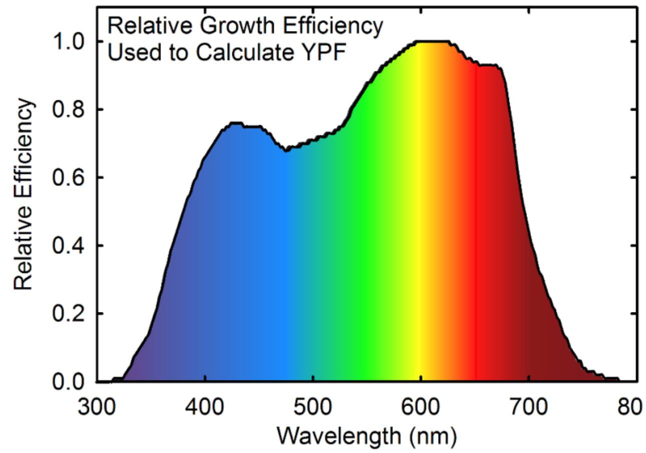

Figure 3. Yield photon flux curve. Effect of wavelength on relative photosynthesis per incident photon for a single leaf in low light [4].

The YPF curve, however, was developed from short-term measurements made on single leaves in low light. Over the past 30 years, numerous longer-term studies with whole plants in higher light indicate that light *quality* has a much smaller effect on plant growth rate than light *quantity* [6,7]. Light quality, especially the fraction of blue light, can be used to control cell expansion rate, leaf expansion rate, plant height and plant shape in several species [8–10], but it has only a small direct effect on photosynthesis. The effects of light quality on fresh or dry mass in whole plants typically occur low or no sunlight conditions, and are caused by changes in leaf expansion and radiation capture during early growth [6].

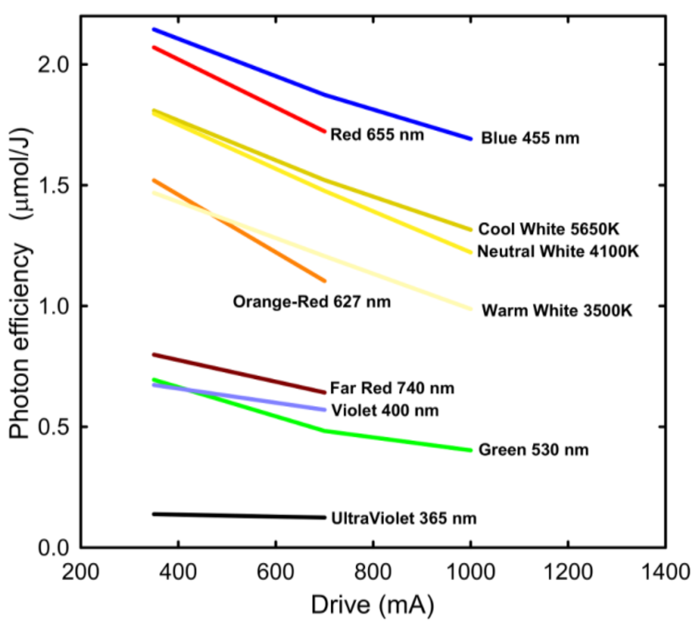

Figure 4. Effect of drive amperage and color on photon efficiency of LEDs. Data for Philips Lumileds LEDs (April 2013), courtesy of Mike Bourget, Orbitec.

Unique aspects of LED fixtures. The most electrically efficient colors of LEDs, based on moles of photosynthetic photons per joule, are blue, red, and cool white, respectively (Fig. 4), so LED fixtures generally come in combinations of these colors. LEDs of other colors can be used to dose specific wavelengths of light to control aspects of plant growth [11], due to their monochromatic nature (see [12] for a review of unique LED applications). Ultraviolet (UV) radiation is typically absent in LED fixtures because UV LEDs reduce fixture efficiency. Sunlight has 9% UV (percent of PPF), and standard electric lights have 0.3 to 8% UV radiation (percent of PPF)[5]. A lack of UV causes disorders in some plant species (e.g. Intumescence; [13]) and this is a concern with LED fixtures when used without sunlight. LED fixtures for supplemental photosynthetic lighting also have minimal far-red radiation (710 to 740 nm), which decreases the time to flowering in several photoperiodic species [14]. Green light (530 to 580 nm) is low or absent in most LED fixtures and these wavelengths better penetrate through the canopy and are more effectively transmitted to lower plant leaves [15]. The lack of UV, green, and far-red wavelengths, however, should be minimal when LEDs are used in greenhouses, because most of the radiation comes from broad spectrum sunlight.

Our objective is to help growers and researchers select the most cost effective fixture options for supplemental lighting in greenhouses. To achieve this goal we measured two fundamental components of each fixture: 1) the efficiency of conversion of electricity to photosynthetic photons that are delivered to a horizontal surface below the lamp, and 2) the distribution pattern of these photons below the fixture.

Materials and Methods

Fixture efficiency. Measurements of fixture efficiency (lamp, luminaire, and ballast) were made by integrating sphere and flat-plane integration techniques. The integrating sphere measurements were made by a testing laboratory (TÜV SÜD America) that specializes in the measurement of the efficiency of lighting fixtures. Radiation measurements are calibrated to NIST reference standards. These measurements of fixture efficiency are considered repeatable to within 1 %.

Flat plane integration. Measurements were made in a dark room with flat black walls using a quantum sensor (LI-COR model LI-190, Lincoln, NE, USA), that was calibrated for each fixture with an NIST-traceable calibrated spectroradiometer. This calibration is necessary to correct for small spectral errors (± 3%) in the quantum sensor that occur because of imperfect matching of the ideal quantum response [16]. Measurements were made in three radial, straight lines below a level fixture and spatially integrated to determine total photon output. Measurements were made 2.5 cm apart near the center, increasing to 10 cm near the perimeter as PPF variation decreased. Fixtures were mounted 0.7 meters above the surface and measurements were made up to a 1.5 meter radius from the center and extrapolated farther using an exponential decay function. The flat-plane integration measurements were used to quantify the pattern of photon distribution from the fixture. Total fixture output from these measurements was similar to measurements made using an integrating sphere (Table 2). When redundant measurements were available, the integrating sphere measurements were used to quantify fixture efficiency.

Cost of electricity. In the United States, commercial electric rates vary widely by region, ranging from $0.07 in Idaho to $0.15 in New York, with residential rates averaging $0.02 higher, and industrial rates $0.02 lower. Electric rates in Europe, and many other countries, can be more than double the rates in the United States. As electricity becomes more expensive, improved lighting becomes more valuable. See U.S. Energy Information Administration for a summary of current electric rates by state and region (accessed April 2013). We used a discounted cash flow model assuming a 5% per year cost of capital on future electrical costs.

Table 2. Efficiency of fixtures using flat-plane integration compared with measurements in an integrating sphere.

	TÜV SÜD America integrating sphere			USU[z] flat plane integration			comparison TÜV/USU[y]
Light	Watts in	Photon output	µmol/J	Watts in	Photon output	µmol/J	(µmol/J)/(µmol/J)
Gavita Pro 1000DE	1033	1751	1.70	1041	1814	1.74	2.7%
ePapillion 1000W	1041	1767	1.70	1037	1937	1.87	9.1%
LSG violet	384	653	1.70	391	628	1.61	-6.0%
SPYDR 600	326	541	1.66	332	575	1.73	4.4%
LSG red/white	390	634	1.63	397	601	1.51	-7.5%
Illumitex NeoSol	279	390	1.40	281	386	1.38	-1.8%
ParSource GLXII	1026	1334	1.30	1008	1433	1.42	8.6%
Lumigrow Pro 325	304	390	1.29	304	355	1.17	-10.1%
California Light Works SOLARSTORM	337	350	1.04	343	331	0.96	-7.7%
Black Dog BD360U	339	339	1.00	346	323	0.93	-7.2%
Apache AT120WR	169	163	0.96	167	150	0.90	-7.2%
iGrow 400W	394	374	0.95	397	354	0.89	-6.5%
Lumigrow es330	318	284	0.90	317	270	0.85	-5.1%
Hydrogrow Sol 9	423	378	0.89	430	396	0.92	2.9%

[z]-Utah State University

[y]-The flat-plane integration may have made an inadequate number of measurements to fully characterize the output of some of the lamps.

Results

The photon efficiency (micromoles per joule) and cost per mole of photons for four categories of lighting technologies (HPS, LED, ceramic metal halide, and fluorescent), in 22 fixtures, are shown in Table 3. This table also shows the five-year electric plus fixture costs per mole of photons. Most fixtures (lamp, luminaire and ballast) are now more efficient than the common 1000-W magnetic-ballast, mogul-base HPS fixtures (i.e. Sunlight Supply, 1.02 µmol per joule). If photons coming out of the fixture at all angles are considered (±90°), the capital cost of the best 400-W LED fixtures is five to seven times more per photon than the 1000-W, double-ended, electronic ballast HPS fixtures (Table 3). This makes the five year cost per mole of photons almost twice that of LED fixtures (Table 3 and Fig. 5A).

Table 3 assumes that all of the photons emitted from the fixture are absorbed by plant leaves. In Table 4, the area under the fixture in which the

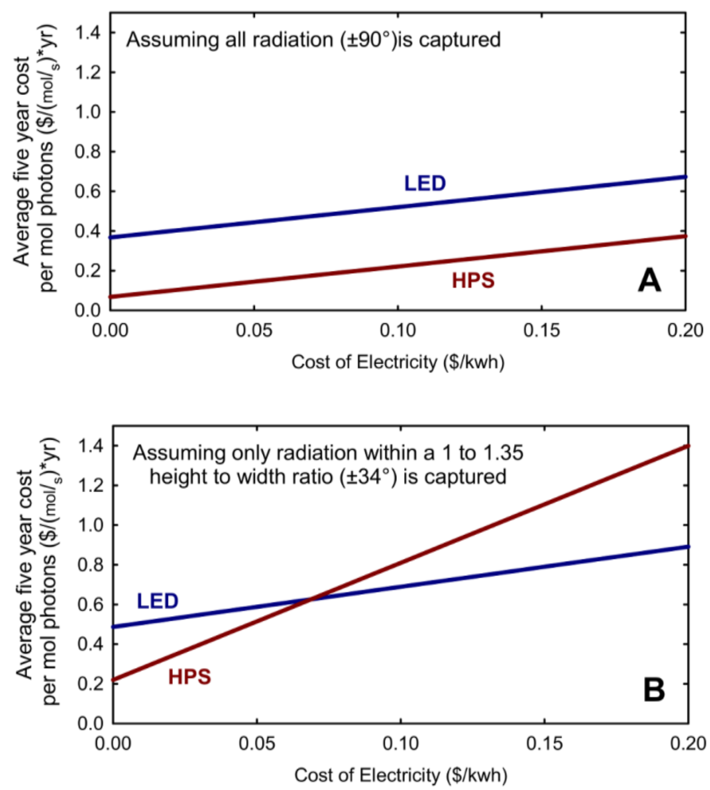

Figure 5. Effect of electricity cost on average five year cost for two capture assumptions. (A) When all radiation is assumed captured, HPS fixtures (Gavita) have a lower five-year cost per photon than LEDs (Red/Blue fixture, Lighting Sciences Group). (B) When only a narrow region below the fixture (±34°) is considered to be captured (e.g. on benches), the LEDs can have a lower cost per photon then HPS fixtures, but the cost per photon increases for both fixtures.

Table 3. Photon efficiency and cost per mole photons, assuming all photons are capture by plants.

Lamp type and Ballast	Fixture producer[z]	Electrical input (J/s or watts)	Photon output[y] (µmol/s)	**Photon efficiency[x] (µmol/J)**	Cost of one fixture[w] ($)	Fixtures needed per mmol/s[v]	Fixture cost per mol/s $/(mol/s)	Electric cost per mol photons[u] $/(mol/s)yr	**Five year electric cost per mol photons[t] $/(mol/s)yr**
High Pressure Sodium									
400 W magnetic	Sunlight Supply	443	416	**0.94**	$200	2.40	$0.48	$0.35	**$0.40**
1000 W magnetic	Sunlight Supply	1067	1090	**1.02**	$275	0.92	$0.25	$0.32	**$0.33**
1000 W magnetic	PARsource GLXI	1004	1161	**1.16**	$350	0.86	$0.30	$0.29	**$0.31**
1000 W electronic	PARsource GLXI	1024	1333	**1.30**	$380	0.75	$0.29	$0.25	**$0.28**
1000 W electronic	PARsource GLXII	1026	1334	**1.30**	$310	0.75	$0.23	$0.25	**$0.27**
1000 W electronic	Gavita	1033	1751	**1.70**	$500	0.57	$0.29	$0.19	**$0.23**
1000 W electronic	ePapillon	1041	1767	**1.70**	$600	0.57	$0.34	$0.19	**$0.24**
LED									
red/ blue	LSG	384	653	**1.70**	$1,200	1.53	$1.84	$0.19	**$0.54**
red/ white	BML	326	541	**1.66**	$1,000	1.85	$1.85	$0.20	**$0.54**
red / white	LSG	390	634	**1.63**	$1,200	1.58	$1.89	$0.20	**$0.55**
red/ white	Illumitex	279	390	**1.40**	$1,400	2.56	$3.59	$0.24	**$0.92**
red/ white/ blue	Lumigrow (Pro 325)	304	390	**1.29**	$1,000	2.56	$2.56	$0.26	**$0.73**
red/ white	California Lightworks	337	350	**1.04**	$1,000	2.85	$2.85	$0.32	**$0.85**
multiple	Black Dog	339	339	**1.00**	$950	2.95	$2.80	$0.33	**$0.85**
red/ white	Apache	169	163	**0.96**	$860	6.14	$5.28	$0.34	**$1.35**
red/ blue	Lumigrow (ES330)	318	284	**0.90**	$1,200	3.52	$4.22	$0.37	**$1.16**
red/ white	Hydrogrow	423	378	**0.89**	$1,300	2.64	$3.44	$0.37	**$1.01**
Ceramic Metal Halide									
315 W 3100 K	Cycloptics	337	491	**1.46**	$640	2.04	$1.30	$0.23	**$0.46**
315 W 4200 K	Cycloptics	340	468	**1.38**	$640	2.14	$1.37	$0.24	**$0.48**
2@315 W 3100 K	Boulderlamp	651	817	**1.25**	$1,000	1.22	$1.22	$0.26	**$0.47**
Fluorescent									
400 W	iGrow	394	374	**0.95**	$1,200	2.68	$3.21	$0.35	**$0.94**
60 W	T8	58	48	**0.84**	$40	20.77	$0.83	$0.40	**$0.51**

[z]- See Table 5 for more information.

[y]- Integrated total photon output of fixture.

[x]- Photon Output per Electrical Input (µmol per second divided by joules per second).

[w]-Cost of fixtures as of April 2014.

[v]-The number of fixtures to get a total photon output of one mmol (1000 µmol) of photons per second.

[u]-Assumes 3000 hours per year operation and $0.11/kWh.

[t]-Cost of fixture (multiplied by fixtures needed) plus cost of electricity over 5 years. We used a discounted cash flow model assuming a 5% per year cost of capital.

Table 4. Cost per mole photons for three capture assumptions.

Lamp type and Ballast	Fixture producer[z]	Assuming all radiation (±90°) is captured: Fixtures needed per mmol/s[y]	Assuming all radiation (±90°) is captured: Five year electric cost per mol photons[x] $/(mol/s)yr	Assuming radiation within a 1 to 2.38 height to width ratio (±50°) is captured: Fixtures needed per mmol/s[y]	Assuming radiation within a 1 to 2.38 height to width ratio (±50°) is captured: Five year electric cost per mol photons[x] $/(mol/s)yr	Assuming radiation within a 1 to 1.35 height to width ratio (±34°) is captured: Fixtures needed per mmol/s[y]	Assuming radiation within a 1 to 1.35 height to width ratio (±34°) is captured: Five year electric cost per mol photons[x] $/(mol/s)yr
High Pressure Sodium							
400 W magnetic	Sunlight Supply	2.40	$0.40	3.99	$0.66	8.51	$1.42
1000 W magnetic	Sunlight Supply	0.92	$0.33	1.71	$0.61	3.60	$1.30
1000 W magnetic	PARsource GLXI	0.86	$0.31	1.31	$0.47	2.82	$1.01
1000 W electronic	PARsource GLXI	0.75	$0.28	1.14	$0.42	2.49	$0.92
1000 W electronic	PARsource GLXII	0.75	$0.27	1.33	$0.47	2.81	$1.00
1000 W electronic	Gavita	0.57	$0.23	0.96	$0.38	2.12	$0.84
1000 W electronic	ePapillon	0.57	$0.24	1.46	$0.61	3.47	$1.45
LED							
red/ blue	LSG	1.53	$0.54	1.62	$0.57	2.03	$0.71
red/ white	BML	1.85	$0.54	2.13	$0.62	3.17	$0.93
red / white	LSG	1.58	$0.55	1.67	$0.59	2.09	$0.73
red/ white	Illumitex	2.56	$0.92	2.66	$0.96	3.82	$1.37
red/ white/ blue	Lumigrow (Pro 325)	2.56	$0.73	3.05	$0.87	4.95	$1.42
red/ white	California Lightworks	2.85	$0.85	3.09	$0.92	4.92	$1.46
multiple	Black Dog	2.95	$0.85	4.43	$1.27	8.64	$2.48
red/ white	Apache	6.14	$1.35	6.58	$1.45	8.21	$1.81
red/ blue	Lumigrow (ES330)	2.64	$1.01	2.82	$1.07	4.33	$1.65
red/ white	Hydrogrow	3.52	$1.16	5.05	$1.67	10.70	$3.54
Ceramic Metal Halide							
315 W 3100 K	Cycloptics	2.04	$0.46	5.43	$1.22	19.55	$4.38
315 W 4200 K	Cycloptics	2.14	$0.48	5.72	$1.29	20.71	$4.66
2@315 W 3100 K	Boulderlamp	1.22	$0.47	1.56	$0.60	2.90	$1.12
Fluorescent							
400 W	iGrow	2.68	$0.94	4.69	$1.65	10.17	$3.58
60 W	T8	20.77	$0.51	38.03	$0.93	83.81	$2.05

[z]- See Table 5 for more information.

[y]-The number of fixtures to get 1 mmol (1000 µmol) of photons per second.

[x]-Cost of fixture (multiplied by fixtures needed) plus cost of electricity over 5 years. We used a discounted cash flow model assuming a 5% per year cost of capital.

photons are considered captured by plants is progressively reduced, and the cost per mole of photons increases as more photons are lost around the perimeter. When only highly focused radiation is considered useful (34°), some LED fixtures have a lower cost per photon than the best HPS fixtures (Table 4, Fig. 1, Fig. 5B and Fig. 6), but because photons are lost around the perimeter at this narrow angle, the cost per photon absorbed by plants is much greater. The lowest cost per photon is realized when a large canopy can be arranged to capture the photons.

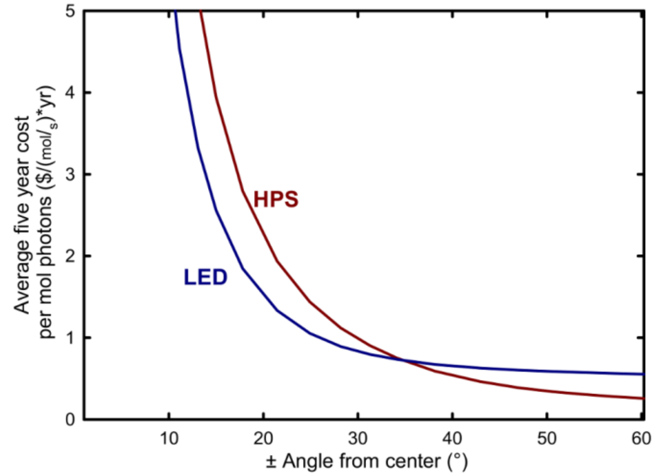

Figure 6. Effect of canopy capture efficiency on average five year cost. The cost per mole of photons for LEDs (Red/Blue LED from Lighting Sciences Group) becomes more favorable than the best HPS fixtures (Gavita) when the lighting area is less than ±35° from center, assuming $0.11 per KWH cost of electricity and 3000 hours per year use.

Discussion

Importance of photon capture. As reviewed in the introduction, lighting system efficiency is the combined effect of efficient fixtures and efficient canopy photon capture efficiency. Precision luminaires, lenses, or adjustable angle LEDs can be used to apply highly focused lighting specifically to the plant growth areas. This is valuable in small greenhouses with widely spaced benches. Canopy photon capture efficiency can be maximized, to above 90%, for large greenhouses with narrow aisles regardless of fixture type**.** The use of LED intracanopy lighting can increase capture rates to near 100%, and may have other beneficial effects such as increased light sharing with intracanopy leaves [17,18]. The concentration of heat from HID fixtures makes intracanopy lighting infeasible with HPS fixtures. Just as precision irrigation can improve water efficiency, precision lighting can improve electrical efficiency.

Effect of fixture shadow. All fixtures block radiation from the sun, and the shadow is proportional to the size of the fixture. For the same photon output, 400-W HPS, ceramic metal halide, fluorescent, and LED fixtures block significantly more sunlight than 1000-W HPS fixtures. We did not include the effect of the shadow in this analysis, but this effect significantly favors the more energy dense, higher wattage HPS fixtures. In the long-term, LEDs can take advantage of innovative design options like mounting along greenhouse support structures, which could provide light without extra shading. Longer, narrower LED fixtures may be preferable to rectangular fixtures because the duration of the shadow is shorter. Fluorescent fixtures, including induction fluorescent, have large shadows relative to their photon output (and have low photon efficiencies) and are therefore generally not economical for greenhouse lighting.

Annual operating costs. Double-ended HPS lamps (1000-W) have a life expectancy of 10,000 hours to 90% survival (based on manufacturer literature), or 3.3 years when used an average of 8 hours per day or 3,000 hours per year (traditional mogul-base lamps have industry reported life expectancies of 10,000 to 17,000 hours, to 90% survival, and cost about $40). The cost of a 1000-W, double-ended replacement lamp is about $140, which averages to $28 per year if we assume a lamp will be replaced once in the first five years. The lamp replacement cost increases to $30 to $35 per year when the labor to replace the bulb is included, but this is small compared to the approximately $600 per year annual electric cost to operate the fixture. Adding the cost of lamp replacement increases the five-year cost of operation by about 5%.

When operated at favorable temperatures, individual LEDs generally have a predicted lifetime (to 70% of the initial light output) of 50,000 hours, about 16.7 years when used an average 8 hours per day or 3000 hours per year. The economic life for LED fixtures has not been established, but replacement of individual LEDs is more expensive than replacing an HID lamp. The life expectancy of LEDs is reduced if they are driven by higher amperage to achieve a higher output, or exposed to high temperatures. Fixtures may be warmed by radiation from sunlight. The cooler the LED temperature, the longer they last. Power supplies, fans, and other components in LED fixtures can fail well before the LEDs themselves and may not be noticed by the user. These components are replaceable, but the labor costs to change LED components increases operating costs.

For these reasons we have not included a differential operating cost between LED and HPS fixtures. We assumed that maintenance costs will be minimal in the first five years for all types of fixtures. Electronic ballasts for 1000-W HPS lamps are still a relatively new technology, and fixtures vary in quality. We have experienced premature failures of LED power supplies, LED circuit boards, HPS lamps, and electronic HPS ballasts in our greenhouse operations. LED fixtures with improved power supplies and optimized operating amperages are available from reputable manufacturers. Improvements in these new technologies are occurring rapidly.

Importance of PPF uniformity. PPF uniformity is critical in many greenhouse applications, especially in floriculture. It is easier to achieve uniformity with fixtures that have broad distribution of photons. Economically, the value of uniform plants may outweigh the cost of wasted photons. Uniformity has been well characterized and modeled with HID lights [19,20], but these techniques have not yet been rigorously applied to LED fixtures. Ciolkosz et al. [21] showed that uniform light on the perimeter of a greenhouse requires higher fixture densities in the outer rows, and consequentially may increase the radiation that is lost beyond the edge of the lighting area, decreasing canopy photon capture. HPS fixtures with narrower focus luminaires are available, but may have lower efficiencies.

Effect of fixture efficiency on heating and cooling costs. Improved electrical efficiency reduces the cooling load in a greenhouse, which increases the value of efficient fixtures when cooling is required. The best HPS and LED fixtures have nearly identical efficiency, so cooling costs are similar for both fixture categories. The ability to rapidly cycle LED fixtures, which prematurely ages other fixture types, could be used to stabilize the heating and cooling load in a greenhouse during partly cloudy days. Rapid cycling could improve temperature control and increase the lifetime of cooling system equipment.

Additional thermal radiation is useful in warming the plant canopy during the heating season, but is detrimental if the canopy is too warm. For this reason, supplemental lighting is usually turned off at mid-day on sunny days.

Conclusions. The most efficient HPS and LED fixtures have equal efficiencies, but the initial capital cost per photon delivered from LED fixtures is five to ten times higher than HPS fixtures. This means that the five-year cost of LED fixtures is more than double that of HPS fixtures. If widely spaced benches are a necessary part of a production system, LED fixtures can provide precision delivery of photons and can be a more cost effective option for supplemental greenhouse lighting.

Manufacturers are working to improve all types of lighting technologies and the cost per photon will likely continue to decrease as new technologies, reduced prices, and improved reliability become available.

Acknowledgments

We thank Peter Nelson and Alec Hay for their dedicated technical work. This work was supported by the Utah Agricultural Experiment Station, Utah State University.

Table 5. Fixture manufacturer and model numbers.

Lamp type and Ballast	Fixture producer	Model number
High Pressure Sodium		
400 W magnetic	Sunlight Supply	Sunstar
1000 W magnetic	Sunlight Supply	Sunstar
1000 W magnetic	PARsource GLXI	GLX I
1000 W electronic	PARsource GLXI	GLX I
1000 W electronic	PARsource GLXII	GLX II
1000 W electronic	Gavita	GAN Electronic 1000W
1000 W electronic	ePapillon	ePapillon 1000W
LED		
red/ blue	LSG (Lighting Sciences Group)	Purple
red/ white	BML	SPYDR 600
red / white	LSG (Lighting Sciences Group)	Vivid White
red/ white	Illumitex	NeoSol NS
red/ white/ blue	Lumigrow (Pro 325)	Pro 325
red/ white	California Lightworks	SolarStorm 400W
multiple	Black Dog	BD360-U
red/ white	Apache	AT120WR
red/ blue	Lumigrow (ES330)[z]	ES 330
red/ white	Hydrogrow	Sol 9
Ceramic Metal Halide		
315 W 3100 K	Cycloptics	All-Bright
315 W 4200 K	Cycloptics	All-Bright w/ 4200k lamp
2@315 W 3100 K	Boulderlamp	Sun-Bright 630W
Fluorescent		
400 W	iGrow	IGF-400W
60 W	T8	Various

[z]-The Lumigrow ES330 was discontinued in 2013.

Literature Cited

1. Bourget CM (2008) An introduction to light-emitting diodes. HortScience 43: 1944–1946.

2. Morrow RC (2008) LED lighting in horticulture. HortScience 43: 1947–1950.

3. Inada K (1976) Action spectra for photosynthesis in higher plants. Plant Cell Physiol 17: 355–365.

4. McCree KJ (1972) The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. Agric Meteorol 9: 191–216.

5. Nelson JA, Bugbee B (2013) Spectral characteristics of lamp types for plant biology. NCERA 101. West Lafayette, IN. Available: http://cpl.usu.edu/files/publications/poster/pub__6740181.pdf. Accessed 27 March 2014.

6. Cope KR, Snowden MC, Bugbee B (2014) Photobiological Interactions of Blue Light and Photosynthetic Photon Flux: Effects of Monochromatic and Broad-Spectrum Light Sources. Photochem Photobiol: In press. doi:10.1111/php.12233.

7. Johkan M, Shoji K, Goto F, Hahida S, Yoshihara T (2012) Effect of green light wavelength and intensity on photomorphogenesis and photosynthesis in Lactuca sativa. Environ Exp Bot 75: 128–133. doi:10.1016/j.envexpbot.2011.08.010.

8. Cope KR, Bugbee B (2013) Spectral effects of three types of white light-emitting diodes on plant growth and development: Absolute versus relative amounts of blue light. HortScience 48: 504–509.

9. Dougher TA, Bugbee B (2001) Differences in the Response of Wheat, Soybean and Lettuce to Reduced Blue Radiation. Photochem Photobiol 73: 199–207.

10. Yorio NC, Goins GD, Kagie HR, Wheeler RM, Sager JC (2001) Improving spinach, radish, and lettuce growth under red light-emitting diodes (LEDs) with blue light supplementation. HortScience 36: 380–383.

11. Yang Z-C, Kubota C, Chia P-L, Kacira M (2012) Effect of end-of-day far-red light from a movable LED fixture on squash rootstock hypocotyl elongation. Sci Hortic 136: 81–86. doi:10.1016/j.scienta.2011.12.023.

12. Massa GD, Kim H-H, Wheeler RM, Mitchell CA (2008) Plant productivity in response to LED lighting. HortScience 43: 1951–1956.

13. Morrow RC, Tibbitts TW (1988) Evidence for involvement of phytochrome in tumor development on plants. Plant Physiol 88: 1110–1114.

14. Craig DS, Runkle ES (2013) A Moderate to High Red to Far-red Light Ratio from Light-emitting Diodes Controls Flowering of Short-day Plants. J Am Soc Hortic Sci 138: 167–172.

15. Kim H-H, Goins GD, Wheeler RM, Sager JC (2004) Green-light supplementation for enhanced lettuce growth under red-and blue-light-emitting diodes. HortScience 39: 1617–1622.

16. Blonquist M, Bugbee B (2013) Analysis of spectral and cosine errors in quantum sensors. NCERA 101. West Lafayette, IN. Available: http://www.apogeeinstruments.com/content/Quantum-Sensor-Poster-Park-City-April-2009.pdf. Accessed 27 March 2014.

17. Frantz JM, Joly RJ, Mitchell CA (2000) Intracanopy lighting influences radiation capture, productivity, and leaf senescence in cowpea canopies. J Am Soc Hortic Sci 125: 694–701.

18. Gómez C, Morrow RC, Bourget CM, Massa GD, Mitchell CA (2013) Comparison of intracanopy light-emitting diode towers and overhead high-pressure sodium lamps for supplemental lighting of greenhouse-grown tomatoes. HortTechnology 23: 93–98.

19. Both AJ, Ciolkosz DE, Albright LD (2000) Evaluation of light uniformity underneath supplemental lighting systems. IV International ISHS Symposium on Artificial Lighting 580. pp. 183–190. Available: http://www.actahort.org/books/580/580_23.htm. Accessed 27 March 2014.

20. Ferentinos KP, Albright LD (2005) Optimal design of plant lighting system by genetic algorithms. Eng Appl Artif Intell 18: 473–484. doi:10.1016/j.engappai.2004.11.005.

21. Ciolkosz DE, Both AJ, Albright LD (2001) Selection and placement of greenhouse luminaires for uniformity. Appl Eng Agric 17: 875–882.