MINNESOTA DEPARTMENT OF COMMERCE
DIVISION OF ENERGY RESOURCES

LED Lighting in Controlled Environment Agriculture

Energy Evaluation, Measurement and Validation

Conservation Applied Research & Development (CARD)
FINAL REPORT

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DISCLAIMER

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Abstract

This research project demonstrated significant reduction in electrical energy utilization and other non-energy benefits resulting from a commercially available light emitting diode (LED) and adaptive control technology system installed in a controlled crop environment.

This project validated energy usage, reported environmental impact and demonstrated other potential plant production benefits to be realized when leafy greens, basil, Swiss chard and cucumbers were grown under LEDs designed exclusively for the horticulture market.

The continuing rapid advancement of solid state lighting (SSL) technology will create more cost-effective greenhouse lighting systems. This trend will produce energy savings that will help the establishment of a sustainable specialty-crop industry in Minnesota.

Safety, security and sanitation of transported specialty crops and impoverished local growers have renewed interest in local production using a cost-effective lighting system to encourage more specialty-crop production in Minnesota.

Light emitting diodes (LEDs) are key to improving energy utilization and production for greenhouse and controlled crop environments. This study was launched to investigate remaining questions about LEDs and to validate unsubstantiated claims made by manufacturers in real-world applications.

Compared to conventional high pressure sodium (HPS) lights, LEDs presented new opportunities to save energy and provide Minnesota growers with affordable, more energy efficient lighting to supplement limited sunlight for greenhouse production so that the growing season can be extended and optimized for increased vegetable production.

Overhead supplemental lighting with high intensity discharge, fluorescent or halogen thermally stresses the tops of the crop and is deficient in red wavelengths that are needed for efficient photosynthesis. LEDs eliminated these specialty crop lighting problems with the same or better plant response and in a more cost-effective manner than traditional lighting.

Outcomes from this technology demonstration suggested LEDs manufactured for controlled environment agriculture could be market ready for inclusion in utility rate-payer funded demand-side management programs. Findings also implied exciting new areas of research for non-energy benefits to be realized, addressing the placement of LED light fixtures for optimized plant production by crop species.

Executive Summary

It is critical to have the right lighting system installed in controlled environment agriculture. This research was commissioned to help understand if light emitting diodes (LEDs) are market ready for this application and to learn how utilities and farmers can benefit from their use.

Growers must carefully evaluate solid-state lighting (SSL) technology and test fixture efficacy under cultivation conditions, especially in the winter when energy costs are high. Continued price reductions in light emitting diodes (LEDs), new product features and consumer demand for locally sourced crops could make the economics of growing crops year-round more viable for Minnesota farmers.

This project investigated 3 primary questions about LED versus high pressure sodium (HPS) lighting in controlled cultivation conditions:

1) whether LED lighting could be used in controlled environments to grow leafy greens, basil, chard and cucumbers to save energy compared to high pressure sodium;
2) how to assess the value of SSL technology as it is fundamentally different than conventional lighting; and
3) what other non-energy outcomes could be expected when plants were grown under LEDs.

Two separate growing environments were constructed using standard greenhouse material hoop construction, draped in black plastic to create a windowless environment. The study was designed so that the only variable was the light source.

The project team determined that 12-months of energy, light and plant monitoring was statistically long enough and repeatable to draw valid conclusions on impacts resulting from growing under the two different lighting technologies. Plant research captured results from three, 12-week growth cycles, evaluating a total of 650 plants.

If energy savings is a goal in controlled environment crops, this research suggested LEDs were the clear winner and more cost-effective compared to HPS. The LED fixtures could be programmed to red, blue or white wavelengths and gave crop growers more options for energy savings and tuned PAR light.

This research validated a 44% energy savings would be realized when crop growing environments were lit with LEDs compared to conventional HPS. The LED lighting system performed better than its stated product specifications in the experimental cultivation area with measured power quality and harmonics that were within recommended industry standards.

This research showed evidence of LED reliability over 6,000 hours of use. Measured light depreciation of LEDs was identified but at a much slower rate than HPS. The high pressure sodium bulbs and a ballast failed twice during the twelve-month study and required additional labor costs to replace.

From an economics standpoint, although they have a higher first cost, LEDs provided a projected net present savings of $5,745 in energy and maintenance costs over the 5-year life of the LED fixtures compared to conventional HPS lighting. Payback from LEDs was estimated to occur in 2.2 years.

The research showed it was possible to produce experimental plants under 100% LEDs with no negative outcomes on plants. Moving plants closer to the light source, thereby increasing light levels in each environment, resulted in greater visual differences in crop species between the two environments and raised the possibility of higher-quality, more compact and possibly nutritionally dense plants produced under LEDs compared with HPS.

Although questions remained around optics and how to tailor LEDs to optimize photosynthesis and plant morphology, the energy efficiency gains were clearly documented from its use in this application.

The project team recommended a deeper understanding of LEDs to promote healthier or stronger rooting systems or disease prevention from light incubation. That could include more study of red, blue and white wavelengths on crops to refine lighting practices so that farmers understand how LEDs could support year-round, local crop production.

The evidence related to plant growth seemed compelling for continued research. LEDs could create a promising new business opportunity for greenhouses, urban agriculture and vertical farming in the State of Minnesota. Production outcomes from studying more plant cycles and a larger sample size could better define ideal LED fixture placement by crop so that LED lighting best practices can be developed for high tunnel production.

Introduction & Background

Energy conservation in controlled environment agriculture is a major concern for food production, especially in winter months. Future generation LED fixtures could achieve even higher levels of efficiency while offering other new benefits to crop growers using high tunnel propagation.

Novel lighting technologies have increasingly been developed for use in controlled environment agriculture. Growers do not have much experience using these technologies in real-world applications.

Light emitting diodes (LEDs) promise to offer substantial energy and maintenance cost savings for greenhouses using supplemental lighting. When used as sole-source lighting to grow plants in closed environments or vertical farms, other benefits of LEDs might be realized including extending the growing season, prolonged daylight, wavelength specificity, cool emitting surfaces, faster cycle times or more healthy growth.

The research was funded to evaluate whether LEDs are market ready to be included in the Conservation Improvement Program (CIP) as a proven energy efficiency improvement strategy for crop growers in Minnesota.

Outsourced Innovation was commissioned by the Minnesota Department of Commerce to complete an 18-month measurement and validation project and communicate outcomes. Research findings were expected to help stakeholders understand the variation in LED performance and compare the robustness of LEDs and benchmark against conventional lighting applied in controlled environment crop production.

Other project collaborators included the University of Minnesota-Department of Horticulture and Tangletown Gardens, which provided greenhouse space for the applied research.

The purpose of the research was to compare and characterize the performance of commercially available LED and adaptive lighting systems designed specifically for greenhouses against conventional high pressure sodium (HPS) lighting system to grow basil, chard, lettuce and cucumbers in a controlled environment.

The project measured and validated the energy savings and characterized plant cultivation outcomes under the two different light sources. It also demonstrates that despite higher first cost, LED technology could be the least cost lighting solution from a total lifecycle cost standpoint.

A secondary research objective was to begin to characterize light impacts on plant growth resulting from different light intensities and wavelength of LEDs versus HPS. The study was launched because questions remained unanswered about this new technology and to validate unsubstantiated claims made by LED manufacturers in real-world growing environments.

The research showed how the plants responded to the white, blue and red light wavelengths from the two fundamentally different lighting systems. Of primary importance was to have experimental plants grown with identical treatments so that electric load was measured and compared, and to determine whether the lights created positive or detrimental plant outcomes.

Terms & Definitions

Adaptive Lighting - Lighting that varies light levels automatically and precisely in response to changes such as the level of use or occupancy of a specific location.

Chlorophyll, the most abundant plant pigment and is most efficient in capturing red and blue light.

Color Temperature – Commonly referred to as Kelvin or color temperature of visible light. Color temperatures over 5,000 K are cool (bluish white, shorter wavelengths) while lower color temperatures are warm (red through warm white, longer wavelengths).

Controlled Environment Agriculture – Producing plants in a greenhouse or other space.

CO2 Response – Plants build tissue through photosynthesis to take carbon from the air around them. More carbon dioxide should mean more rigorous plant growth.

Design Light Consortium (DLC) – Collaborative electric industry association to pre-qualify LED products on performance and energy efficiency through guidelines so that energy efficiency products don't fall short on quality.

Foot candle (Fc) – A unit of illuminance equal to one lm/ft^2 or 10.76 lux

Illuminance – The density of the luminous flux incident at a point on a surface measured in lux or foot candle that can include horizontal illuminance and vertical illuminance.

Illuminating Engineering Society of North America (IESNA) – An industry authority on illumination and supporting standards related to the art and science of lighting.

Harmonic Distortion – Indicates how much harmonic current is flowing in the power lines. Can create additional voltage and power losses in transmission lines. Energy Star standard for LEDs established at < 20%.

High Intensity Discharge (HID) – Traditional lighting technology that produces intense light by means of an electric arc between tungsten electrodes housed inside a tube, which requires a ballast. Three most common forms are metal halide (MH), high pressure sodium (HPS) and mercury vapor (MV).

High Tunnels – Low cost season extension technology that is passively vented and heated structure and used for producing a diversity of horticulture crops.

Light Emitting Diodes (LEDs) – A semiconductor device (diode) that emits visible light when an electric current passes through it.

Lighting Facts Label – Lighting industry label important to consumers that describes lighting products on 6 parameters including lumens, efficacy, wattage, correlated color temperature, color rendering, and LED light source lumen maintenance.

Light pollution – The scattering of electric light into the atmosphere, usually caused by luminous flux above the horizontal plane.

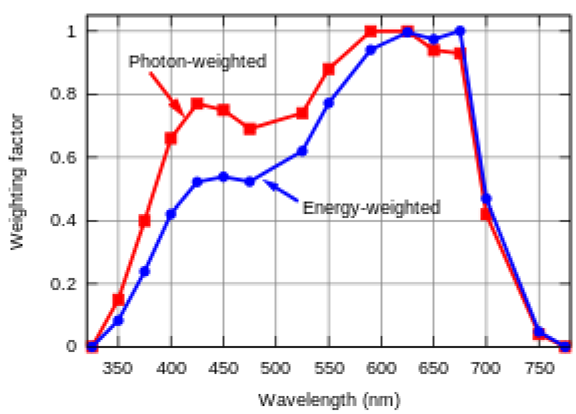
Light trespass – Light that strays from its intended purpose, causing visual annoyance.

Photosynthetic Active Radiation (PAR) light - designates the spectral range (wave band) of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis. This spectral region corresponds more or less with the range of light visible to the human eye. Photons at shorter wavelengths tend to be so energetic that they can be damaging to cells and tissues, but are mostly filtered out by the ozone layer in the stratosphere. Photons at longer wavelengths do not carry enough energy to allow photosynthesis to take place.

Photons – Light energy measured in short or long wavelengths. PAR is normally quantified as mols or µmol photons $m^{-2}s^{-1}$, which is a measure of the photosynthetic photon flux (area) density, or PPFD. For example, a light source of 1000 lm at a color temperature of 5800 K would emit approximately 1000/265 = 3.8 W of PAR, which is equivalent to 3.8*4.56 = 17.3 µmol/s.

Photon Flux - The light wavelength that will cause photosynthesis action in plants. If the exact spectrum of the light is known, the photosynthetic photon flux density (PPFD) values in µmol/s can be modified by applying different weighting factor to different wavelengths. The red curve in the graph shows that photons around 610 nm (orange-red) have the highest amount of photosynthesis per photon. However, because short-wavelengths photons carry more energy per photon, the maximum amount of photosynthesis per incident unit of energy is at a longer wavelength, around 650 nm (deep red). See Figure 1.

Figure 1 - Photon Flux



Photopic Vision - Light adapted vision that occurs at moderate and high levels of luminance or at greater than 3.4 cd/m² to permit discrimination of colors and mediated by the cone receptors in the retina of the eye.

Power Factor – A measure of how efficiently electric power is being used within a facility electrical system. Energy Star standard for high-quality LEDs is >.90.

Relative Quantum Efficiency - Considers the photosynthetic rate of a plant by measuring three things: 1) CO 2 uptake, 2) the energy of light at different wavelengths and 3) the plants' absorption of light.

Scotopic Vision – Vision mediated essentially or exclusively by the rod receptors in the retina of the eye and generally associated with adaptation to a luminance below 0.034 cd/m².

Solid State Lighting (SSL) – Lighting technology that uses semiconductor devices (or LEDs) with no glass bulbs, no pressurized gasses and no electrical filament to produce intense light.

Research Methodology

The research and production areas were established at Tangletown Gardens, LLC, County 9 Road, Plano, Minnesota 55370. The farm was exploring new energy efficient lighting technologies to support year-round production and farm-to-table initiatives.

Tangletown Gardens currently provides produce to Southwest Minneapolis Wise Acres Eatery, about 40 miles away.

Materials and equipment for the space were designed to be statistically large enough so that conclusions could be broadly applied to any controlled environment agriculture facility within Minnesota. The research site occupied 288 square feet of segregated cultivation space within an existing greenhouse at Tangletown Gardens.

Two separate propagation environments were constructed using standard greenhouse material hoop construction, 100 feet long by 30 feet wide draped in black plastic to create a windowless environment. The research facility was divided into 2 separate test cells, each measured 144 square feet in size as illustrated in Figure 2. Each cultivation area measured 6 feet x 24 feet.

Figure 2- Research Facility

The study was designed so that the only variable was the light source. To create a dark, windowless facility, both growing areas were covered with black plastic sheeting on the inside hoop within the propagation area and white plastic sheeting draped over the outside hoop to reduce heat.

The project team captured results from three, 12-week growth cycles, evaluating a total of 650 plants. The project team determined that this crop size was statistically large enough and repeatable to draw valid conclusions on plant impacts resulting from growing crops under two different lighting technologies.

The lighting system and electrical equipment was installed over a three day period and completed on March 20, 2014. Fixtures were installed at 8 feet-4 inches above grade, 4 fixtures were mounted in each test cell, according to specifications provided by the lighting manufacturer (see Appendix A).

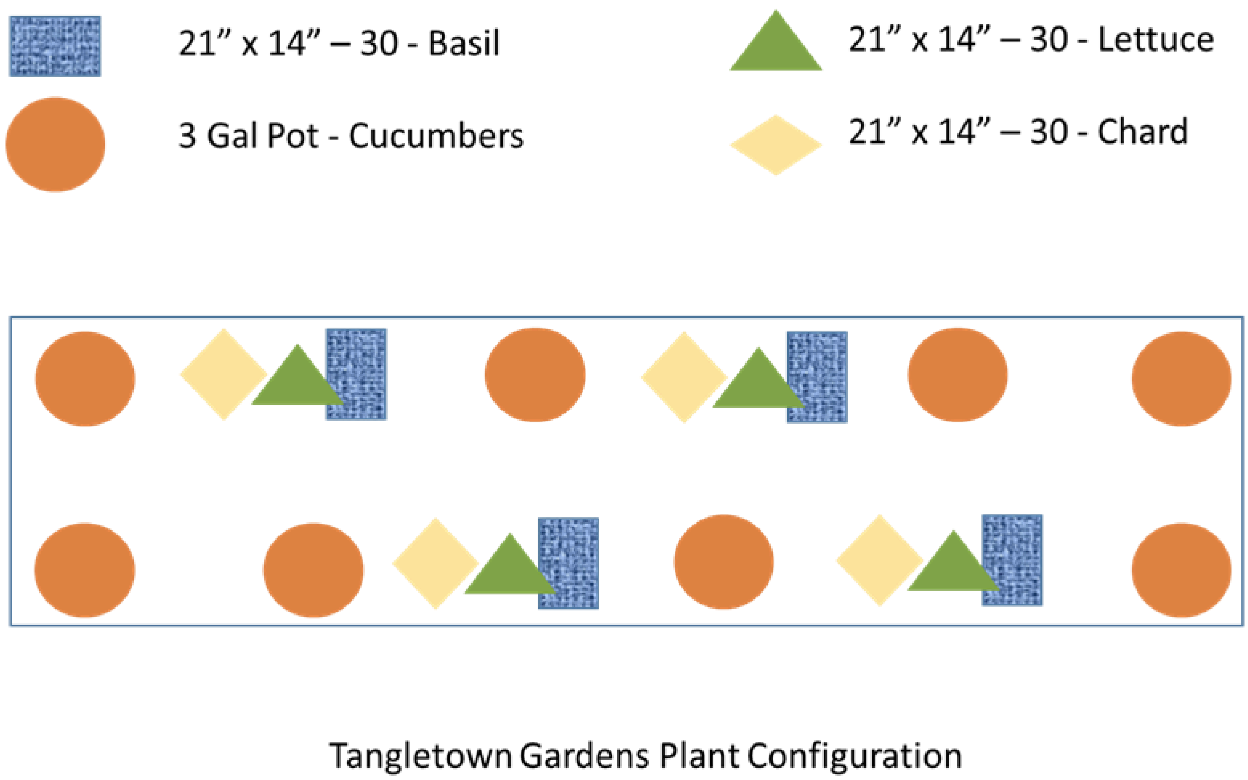
Cell 1 was illuminated with 4- 650 watt LED light fixtures manufactured by LumiGrow.

Cell 2 was illuminated with 4 – 1,000 watt HPS fixtures manufactured by Earthworks. Lights were mounted at the same overhead position, 8 feet 4 inches above ground and 6 ½ feet between fixtures.

Seedlings trays were situated on the ground between 7 feet to 7 ¾ feet away from the light source.

The layout of seedling trays and plant pots within each cell is illustrated below in Figure 3. Cycles began with 30 seedlings in each tray and 1 cucumber in each 3-gallon pot.

Figure 3 – Tangletown Gardens Plant and Flat Setup



Energy use measurement equipment included a utility-grade power meter manufactured by DENT (ElitePro), and data loggers. Light measurement required a commercial grade meter: a Solar Light radiometer (Model #2100) with photopic / scotopic sensors and PAR data loggers (±5% margin of error).

Lighting field measurements followed standard research protocol as outlined by Illuminating Engineering Society of North America (IESNA)[1] and the American Society of Agriculture and

[1] Jianzhond, Jiao , PhD, The Latest in LED Test Methods & Standards, Osram Opto Semiconductors.

Biological Engineers.[2] The same lighting engineer, dressed in black performed all three data collections throughout the 12-month study to ensure consistent measurements and no light trespass.

The research was launched on March 22, 2014 with all the lights, fans and energy monitoring equipment energized along with the planting of Cycle 1. The test results from Cycle 3 concluded on March 12, 2015.

Energy and Electrical

A single phase, 120-220 VAC electrical panel was installed to support the lighting and HVAC systems. Six 20 amps circuits (Figure 4) supported the electrical load needed for the entire research area.

A utility-grade Dent ElitePro meter was installed inside the electrical panel to measure input wattage, power factor and total harmonic distortion for each lighting system (Figure 4). Excessive power draw of the HPS lighting forced only two of four fixtures to be monitored. Two HPS fixtures were connected to Channel 1 of the Dent meter and two (of four) LED lamps were connected to Channel 2. Energy consumption data that was captured from Channels 1 and 2 were doubled to report electric load within the HPS and LED test cells.

Figure 4- Six Circuits, 20 Amps each, 4 Channels

Energy use data files were captured in 15-minute intervals. Data was summarized quarterly during the three growth cycles (spring, fall and winter).

The blower and fans for the LED cell and HPS cell were connected to Channel 3 and Channel 4, respectively. The luminaries and fan systems were installed according to the electrical diagram in Figure 7.

Test Cell 1 housed 4 LumiGrow LED luminaires (Figure 5) measuring 24 inches x 18 inches and mounted at a height of 8'-4" feet above floor grade.

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[2] Lighting Systems for Agriculture Facilities, American Society of Agriculture & Biological Engineers (ASAE) EP344.3, Jan 2005.

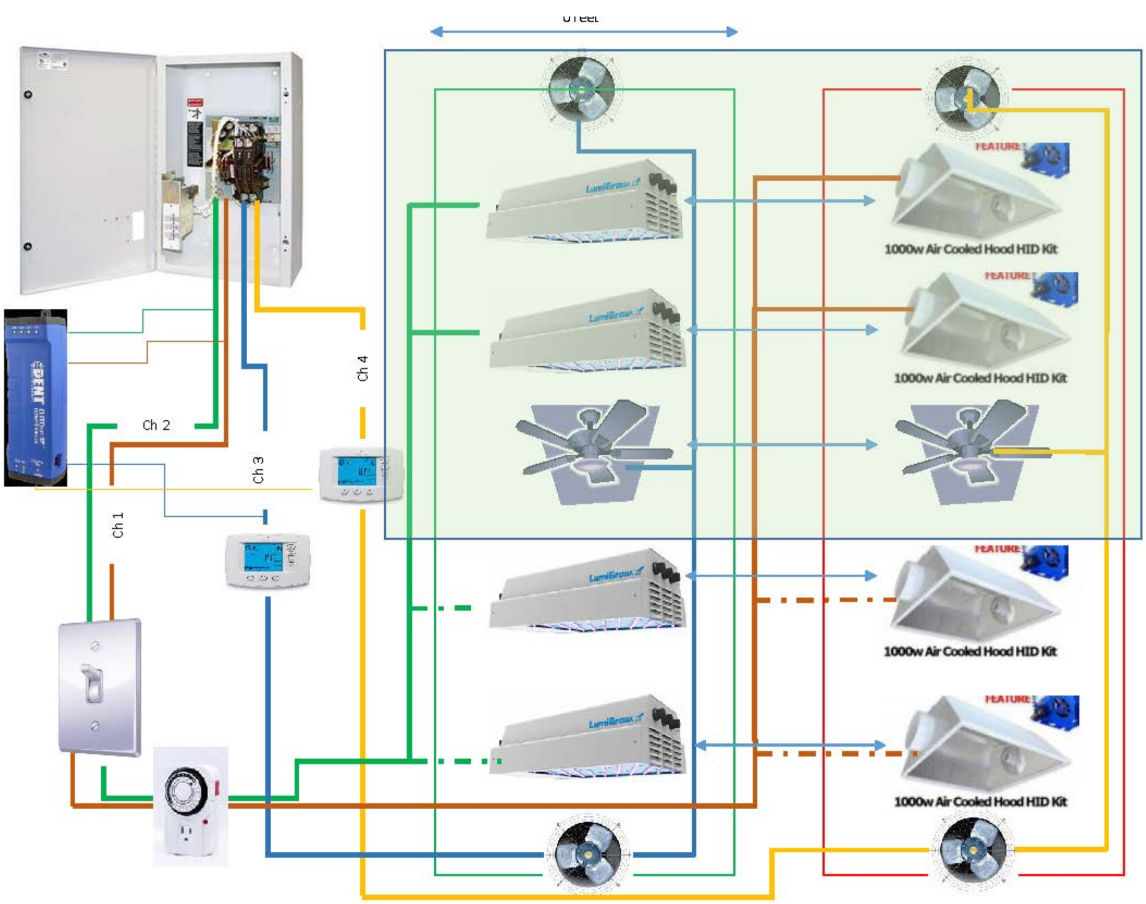
Test Cell 2 housed four Earthworth Grow Lighting luminaires (Figure 6) measuring 13 ½ inches x 8 inches x 8 1/2 inches also mounted at 8'-4" feet above floor grade.

The lighting photoperiod was configured for 18 hours each day, 7 days of the week, set between 6:00 am and midnight.

Figure 5 - LED Fixture

Figure 6 - HPS Fixture

Figure 7 - Wiring and Electrical Schematic



Test Cells 1 and 2 were installed with a blower fan, air inlet, air exhaust and a digital thermostat to regulate the temperature. The entire system was connected and wired as shown in Figure 7. Ambient room temperature for the growing areas were maintained at or under 80 degrees.

Mounting locations of 4 luminaires, 2 fans, fresh air inlet and exhaust were installed identically in Cell1 and Cell 2. Both lighting systems were energized on March 22 2014 at 6:00 a.m.

Electric load was measured as shown in the schematic outlined in Figure 7. Energy usage data was captured from the DENT meter using 4 Channels as follows: Channel 1 – two HPS fixtures, Channel 2 - two LED fixtures, Channel 3 air intake and exhaust fans and overhead fan in LED cell, Channel 4 air intake and exhaust fans and overhead fan in the HPS cell.

Energy usage data that was captured from Channels 1 and 2 were doubled in calculations presented in this demonstration so that the report reflected the total electric load from the 4 LEDs and the 4 HPS fixtures in this study.

Lighting Measurement and Validation

The project team created a 56-point light grid taking measurements at 3 feet above horizontal grade within each test cell as shown in Figure 8. Light output was measured at 74 hours, 4,000 hours and 6,000 hours post installation to monitor lumen depreciation and light uniformity. Outcomes were reported in lumens (foot candles) and PAR light (micro moles per meter squared).

A Solar Light Radiometer (Model #2100) with photopic and scotopic sensors and PAR data loggers (±5% margin of error) captured 56 data points, with locations shown in Figure 8. Light readings from each test cell were captured on the same day and within 90 minutes of each other. Both test cells were created within a greenhouse, with outside light eliminated so there was no light trespass that could skew results.

Figure 8 - Light Grid at Research Site

											Y																	
	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0		
Air Inlet	53		52		45		44		37		36		29		28		21		20		13		12		5		4	6	
																												5	
	54		51		46		43		38		35		30		27		22		19		14		11		6		3	4	
																												3	X
	55		50		47		42		39		34		31		26		23		18		15		10		7		2	2	
																												1	
	56		49		48		41		40		33		32		25		24		17		16		9		8		1	0	
		Door																					Air Exhaust						

Research Design Summary

Hypotheses: LED lighting saves energy compared to HID lighting without compromising plant production outcomes.

Experimental variable: Light source

- Experimental group: LED (LumiGrow Pro 650) -- Test Cell 1
- Control group: HID lighting (Earth Worth Plantanator 1000w with HPS bulbs) – Test Cell 2

Controlled variables:

- Quantity of feed – Water intake
- Nutrients/composts - identical soil used (see Table 8).
- Temperature - each cell connected to a digital thermostat with ambient temperature set at 70 degrees
- Ventilation - each cell independently controlled for air circulation
- Auxiliary HVAC – each cell independently monitored for energy consumption

Research Site Controls

- Windowless test site to ensure no outside light trespass that would skew results
- Control and experimental lighting systems isolated and on separate electric circuit panels.
- Three plant cycles over nine months

Plants and Crop Yield

Field study included a total of 612 plants grown over 288 square feet in a windowless cultivation chamber. Each test cell included 306 plants within a 144 sq. ft. research environment for each lighting system.

Swiss chard, lettuce and basil seedling trays were placed on four-inch tall plastic flats, cucumber pots were placed on two-inch tall plastic flats, on ground level.

Three growth cycles, 12 weeks

- Cycle 1: March – June 2014
- Cycle 2: September – November 2014
- Cycle 3: December – March 2015 **(**Cycle 3 plants moved up 1 foot closer to light source)

Thirty seedlings per plant type and 12 cucumber plant specimens per cycle produced the following total plant population in each test cell:

- 90 Basil
- 90 Leaf Lettuce
- 90 Chard
- 36 Cucumbers

Study Duration

A total of 11.5 months of energy usage data was collected and isolated by light source. Three 12-week growth cycles were statistically large enough to identify impact on plant growth to project outcomes for a larger population of plants. The usable data in this study is from July 1, 2014 through March 11, 2015; due to issues with the HPS lighting system during the first three months of monitoring.[3]

LED and HPS Fixture Installation

Cell 1 plant trays were positioned under four 650-watt LumiGrow Pro fixtures that were mounted eight feet four inches above grade. LED fixtures were set at red/blue settings, each 100%.

Cell 2 plants trays were positioned under four 1000 Watt HPS fixtures at 8 feet 4 inches above grade; Fixtures were established using HPS bulbs at 2100 Kelvin temperature.

Energy modeling

Cells 1 and 2 were set for lights "on" at 6:00 am and lights "off" at 12:00 am to mimic 18 hours/ day photoperiod. Energy data files collected include:

- Input Voltage
- Time
- Line Current
- K Factor
- Forward Current
- Harmonics
- Power Factor.

Electric load and other energy factors of LED versus HID captured BTUs from a light source that produced no forward heat or heat recovery from the back end of LEDs.

Energy Equipment System-level Measurement

A utility-grade DENT meter equipped with 4-channels and a single-phase circuit validated input wattage, power factor and total harmonic distortion of each lighting system with data captured in 15-minute intervals.

[3] Two HPS lamps and one HPS ballast failed during the first three months of monitoring, resulting in unreliable data during this period.

Results: Evaluation, Measurement & Validation

Lights in Controlled Environments

This study measured and compared both photosynthetically active radiation (PAR), light used for photosynthesis, measured in micro moles per meter squared per second, and lumens, reported as foot candles.

Photographic comparisons shown in Figure 9 and Figure 10 demonstrated how the two illuminated test cells were different in color and light output. This was explained by the spectral light composition of LEDs (red and blue) compared with white light produced from HPS.

Figure 9 - LED Lighting in Cell 1

Figure 10 - HPS Lighting in Cell 2

Light is a source of energy and information for plants. Plants react to quality, intensity, duration and direction of light.

LumiGrow's LED fixture has three individually adjustable light channels that could be "tuned" to the right color light depending on the crop species grown; red, blue and white. That feature provided the grower with lights that could be set at either white light or red/blue light to investigate a photosynthesis response.

The project team agreed to program LED fixtures at 100% red and 100% blue for the experimental plants. The study evaluated lettuce, basil, Swiss chard and cucumbers, and benchmarked morphologic and photosynthetic responses against plants grown under HPS fixtures.

The Earth Worth conventional HPS light source did not allow for tuned light but growers could interchange bulbs with either HPS or metal halide.

HPS bulbs are omni-directional and produced white light in all directions within Test Cell 2. Cell 2 was noticeably brighter. Because the LED lights were a point source with optics that directed red and blue light forward with no illumination behind the fixtures, Cell 1 appeared dramatically dimmer.

It is well established that plant productivity in response to red and blue LED lighting can have dramatic effects on crop anatomy and morphology as well as nutrient uptake and pathogen development.[4] Light is needed as energy in photosynthesis and to provide plants critical information about their environment in order to stimulate germination or growth to a certain size or shape. Light induces protective substances and is needed for plants to flower or instigate a change to vegetative growth. Other more recent, peer-reviewed horticulture research suggests that red and blue LED light plant incubators produce better growth and fewer days to flowering in basil compared to growing that crop in greenhouse conditions[5].

In addition to the light spectrum that is visible to humans (400 nm – 700 nm), plants use the red and blue part of the spectrum as their energy source for photosynthesis. The 400 nm–700 nm wavelength range is called "Photosynthetically Active Radiation" or PAR. Much of the light plants need is within this range, but for optimal growth, UV light (280 - 400 nm) and/or far-red light (700-800 nm) is important as well. For example far-red light is critical for flowering in many plants (tomatoes, eggplant, okra, cucumbers) and blue light is best for development of leafy greens (lettuce, basil, chard).[6]

Known photoreceptors are more efficient in the blue and red area of the spectrum. Leafy green plants reflect a significant part of light in the green area of the light spectrum, while absorbing a higher percentage of blue and red light.

Figure 11 - Light Absorption Rate for Plants Versus Humans (measured in Nanometers)

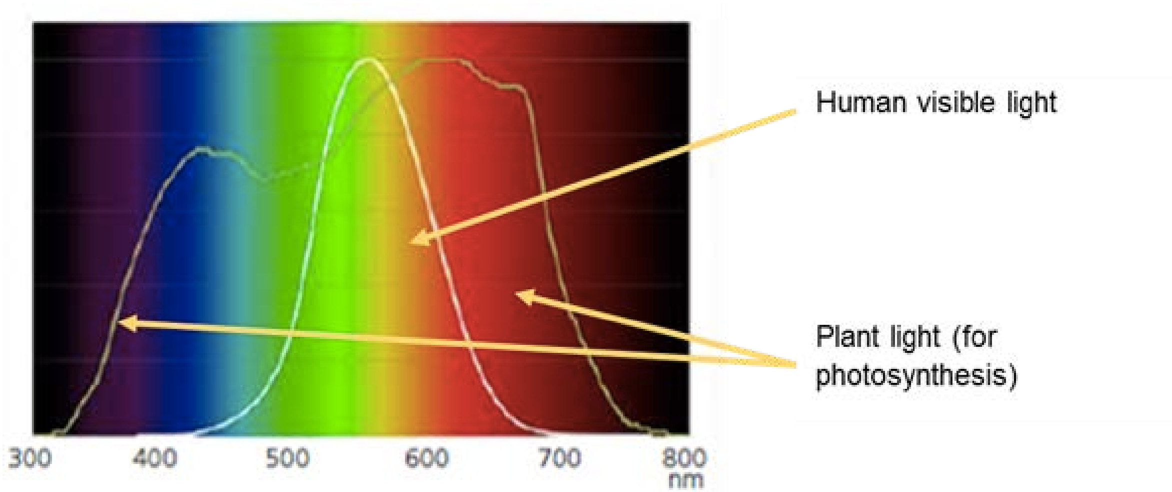


Figure 11 shows the differences between how plants and humans see light wavelengths, measured in nanometers. The y-axis shows light absorption rate to instigate photosynthesis response in plants.

The influence of supplemental light intensity on seedlings and vegetable crop production has been well studied. Relative quantum efficiency considers the photosynthetic rate of a

[4] Massa, et al., "Plant Productivity in Response to LED Lighting," HortScience, December 2008, Vol .43, no 7. p 1951-1956.

[5] Sabzalian, et al., "High Performance of Vegetables and Flowers and Medicinal Plants in Red/Blue LED Incubators for Indoor Plant Production," Agronomy for Sustainable Development, October 2014, Vol. 34, Issue 4, pp. 879-886.

[6] Cornell University Controlled Environment Agriculture (CEA) Program 2014.

plant by measuring three things: 1) CO 2 uptake, 2) the energy of light at different wavelengths and 3) absorption of light.

The Canadian Green House Conference[7] developed recommended ranges of PAR light by crop species, measured as micromoles per meter squared, which are summarized in Table 1 below.

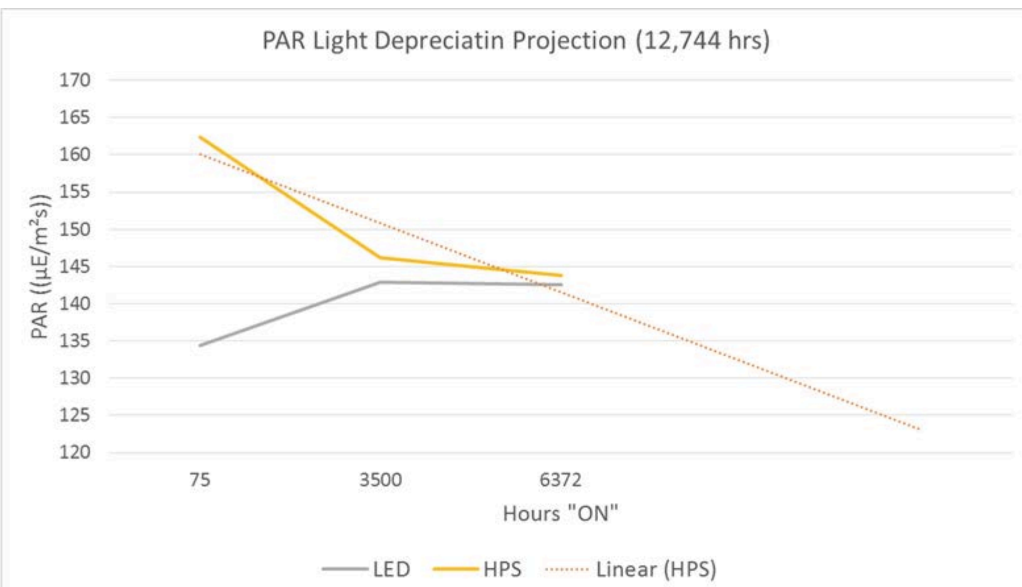
Table 1 - Industry Recommended PAR Light by Crops

Crop	Industry Recommended PAR light ($\mu mol/m^2$)
Lettuce	50-100
Cucumber	120-150
Basil	500
Chard	N/A

Baseline measurements from this project validated that both LED and HPS met industry recommendations with the exception of light required to grow basil. Higher PAR light from both LED and HPS technologies might be more likely to produce basil plants with higher biomass qualities.

At fixture installation, LEDs produced 17% lower measured PAR light than HPS but that changed at 4,000 hours once fixtures were seasoned and produced similar PAR light to HPS. This demonstrated how the two lighting systems behaved once seasoned from illumination. Early light readings revealed how quickly HPS light degraded at 4,000 hours and evidence of longer useful life of LEDs.

Figure 12 - Projected Long-Term PAR Light Depreciation



[7] Dorias, M., "Use of Supplemental Lighting for Vegetable Crop Production: Light Intensity, Crop Response, Nutrition, Crop Management, Cultural Practices," Canadian Greenhouse Conference, October 9, 2003.

Measured PAR light between the two lighting technologies were almost identical at final 6,000 hours (Figure 12). However, the LED light output was stabile compared to a continued decline in light output that was evident in HPS fixtures.

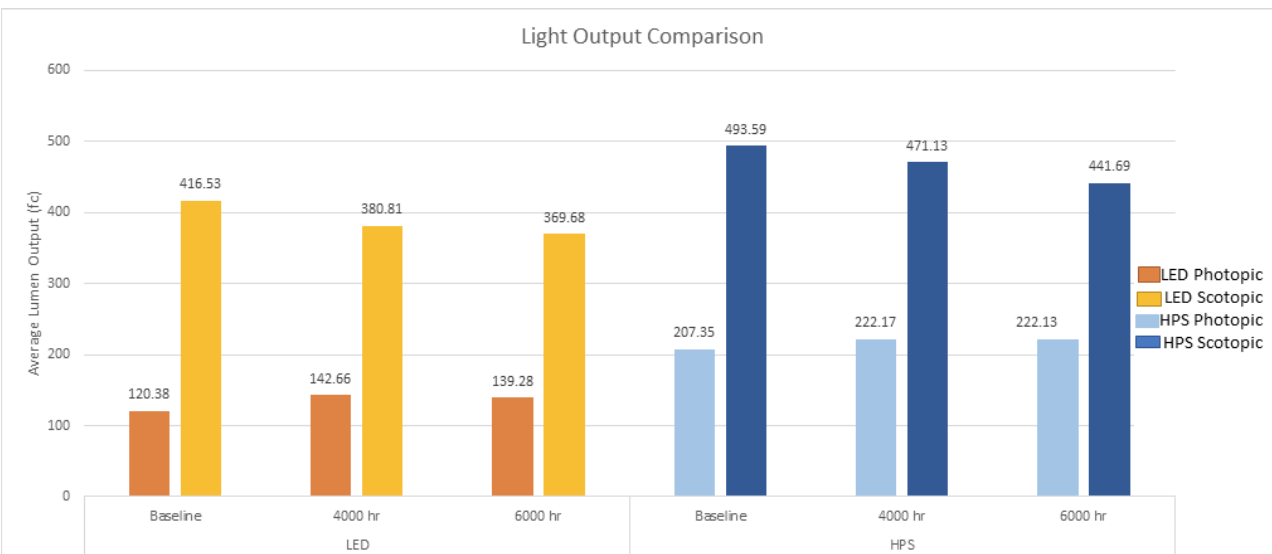
An intriguing finding was the PAR reading for LEDs **increased** by about 6%, and remained closer to recommended PAR lighting standards, while the PAR for HPS **declined** about 10% after 4,000 hours.

Extrapolating light depreciation after 6,000 hours suggested HPS lighting could fall below recommended PAR light for some crops at about 7,000 hours of operation. HPS fixtures have a rated useful life of 24,000 hours versus LEDs that have a rated useful life of 50,000 hours. LED fixtures showed evidence of light stability over time. This is what would be expected when HPS degrade faster.

Lumens or footcandles are common in light measured for people. Photopic and scotopic lumens are visible by humans, using rods and cones in the eye. Lumens are commonly used to express the quantity of light that people work under within a controlled crop environment or a greenhouse using supplemental lighting.

At installation, the HPS fixtures produced as many as 25-50% more photopic and scotopic lumens than the LED lighting system (Figure 13). This explained why it appeared easier for humans to see under HPS lighting in Cell 2.

Figure 13 - Lumen Output Comparisons (foot candles)



At 6,000 hours, the HPS fixtures produced between 15-35% more light in terms of foot candles compared to LEDs.

This project evaluated the use of light for plants versus people. LED fixtures produced both different light wavelengths and fewer lumens (foot candles) compared to HPS fixtures. These qualities were visibly noticeable to the project team throughout the study.

Research implications for growers will be to understand whether supplemental lighting is required for people or plants. Although LEDs produced fewer measured foot candles, it is PAR light that is necessary for plant optimization.

Good lighting practices distribute light evenly across the entire cultivation area. Figure 14 and Figure 14 illustrated light distribution and uniformity within the two cultivation cells by light source.

HPS fixtures provided more uniform lighting within recommended PAR standard (Figure 14) throughout the cultivation cell. LEDs did not distribute light as uniformly. More areas fell below recommended PAR light throughout the LED cultivation cell.

Photosynthesis is directly related to the light level. Plants receiving more PAR light, regardless of HPS or LED, were expected to have higher photosynthesis rates.

Light distribution and intensity varied across both the HPS and LED cultivation areas as shown in Figure 14 and Figure 15.

Figure 14 - HPS PAR Light and Distribution

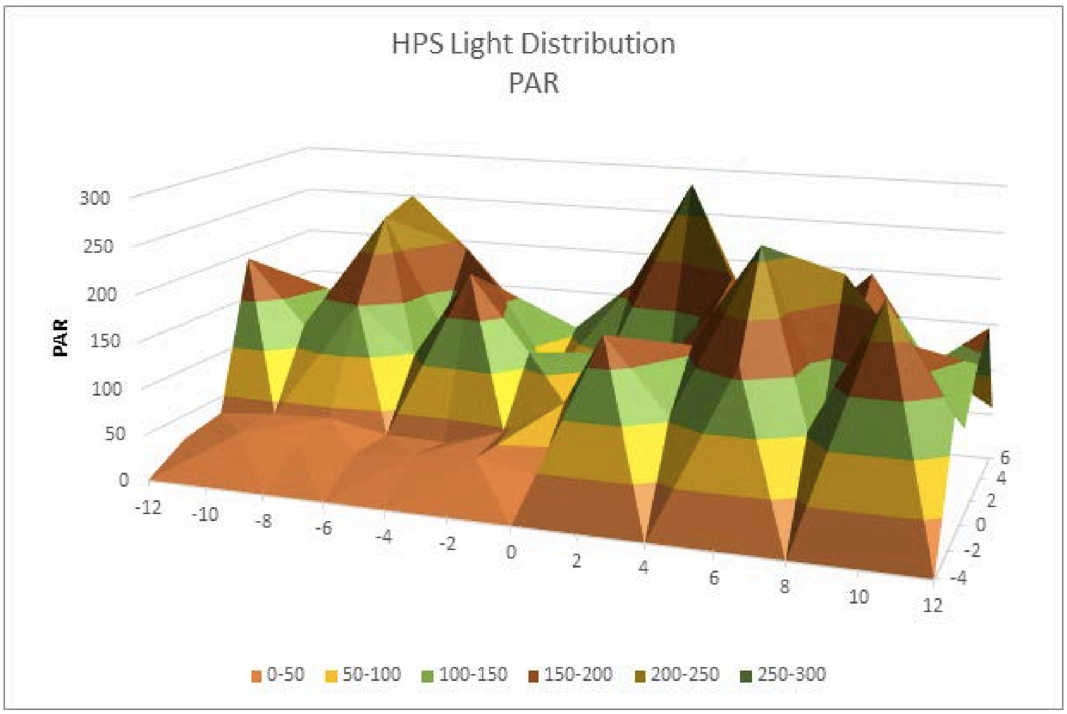
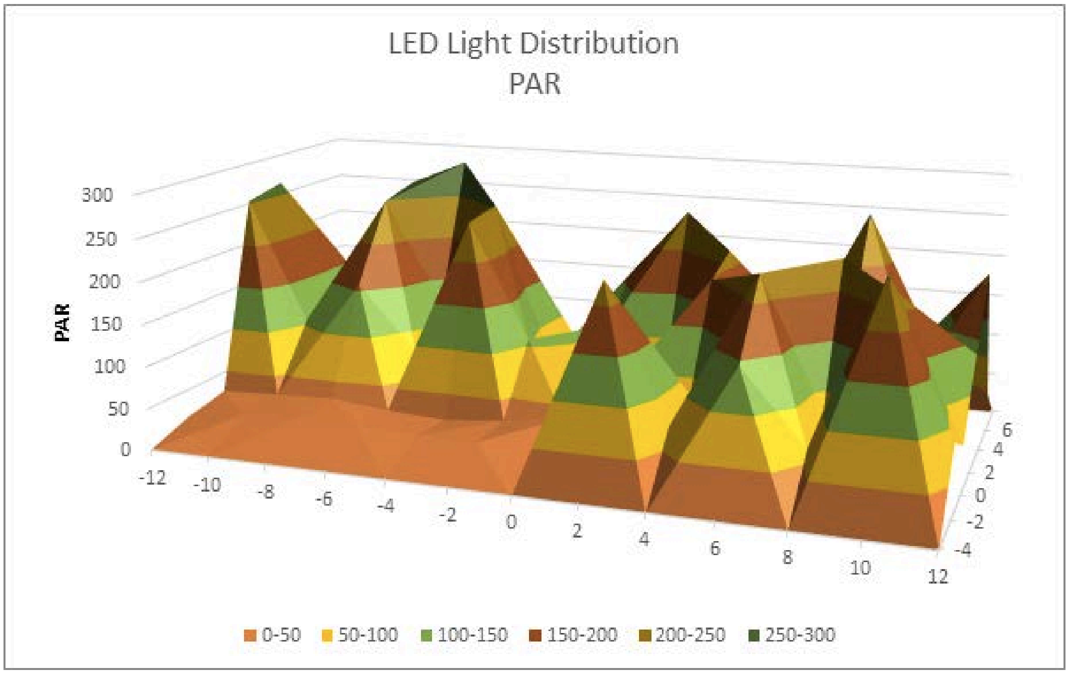


Figure 15 - LED PAR Light and Distribution



PAR light was more intense directly under the HPS and LED fixtures, but not uniform throughout the cultivation areas.

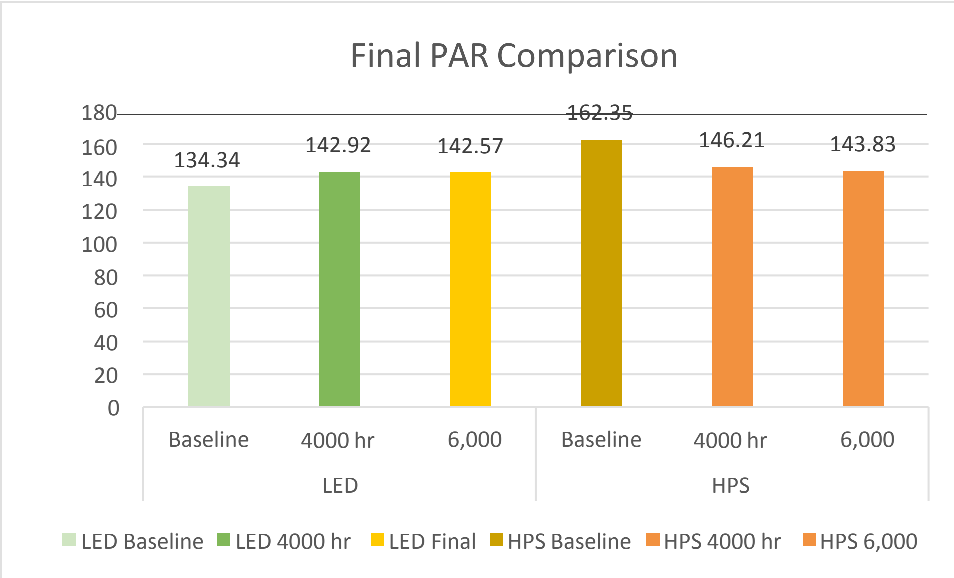
These findings had implications for light placement in this study because light levels over the cultivation trays varied greatly from one flat to another. PAR light was not uniform and distributed differently among flats in the same test cell.

Varied light distribution throughout the cells made it difficult to report a specific plant growth with a high level of confidence in Cycles 1, 2. However, the demonstration suggested a different growth response based on LED versus HPS lighting source when plants were moved 1 foot closer to the light source in Cycle 3.

Because LEDs provide directional lighting, they produced greater light intensity directly under the fixtures but lower overall PAR light throughout the cultivation areas compared to the HPS fixtures. There was more consistent PAR light under the HPS, which is PAR that measures between 100-200 micromoles per meter squared.

Plants respond to maintained PAR light. The project team measured whether the PAR light depreciated between the two lighting systems over 6,000 hours, with outcomes shown in Figure 16.

Figure 16 – Final, PAR Light Comparisons



The research validated almost identical HPS and LEDs PAR light at 4,000 hours and at 6,000 hours of use. The tradeoff was that measured PAR light degraded at every test period for HPS fixtures whereas the LED fixtures showed little if any evidence of light degradation at 6,000 hours of use. This performance explains why LED fixtures have a rated useful life of 50,000 hours compared to 24,000 hours for HPS fixtures.

Measured PAR light of 142 and 143 for LED and HPS, respectively was within recommended lighting standards for cultivating 3 of the 4 crops in this study (Table 2), with the exception of basil, that recommends PAR light of 500 micro moles per meter[8] (see Table 1).

Table 2 - Final Foot candle and PAR Light Readings

Final Reading	Foot candles (Lumens)	PAR Light Micromole meter^2)	% Change in PAR light
LumiGrow LED System	Photopic - 139 Scotopic - 370	142.6	+ 6%
EarthWorks HPS System	Photopic - 222 Scotopic – 442	143.8	-10%

Research implications of lighting in Cell 1 and Cell 2 are as follows:

1. Employee considerations. HPS lights were significantly brighter and produced significantly more human-friendly light (foot candles) necessary for employees working in a controlled environment. The LED cell was visibly darker and difficult for working.

[8] Ibid.

2. Uneven light distribution from LEDs. This implied growth impacts from red or blue LED light was inconsistent or only beneficial to plants located directly under the LEDs fixtures that received the highest PAR intensity.
3. Despite a clear energy savings benefit from using LEDs in this demonstration, a crop specific lighting recipe may be required to achieve optimal results. Growing basil may require more fixtures to achieve recommended PAR in controlled environment agriculture.

Energy Consumption and Power Quality

Energy data files collected using the DENT meter validated a measured energy savings of 44% (lighting system only) when the cultivation area was illuminated with LEDs compared to the HPS system. In fact, this study showed that the LED fixtures exceeded published product specifications for input wattage, power factor and harmonics. Table 3 summarizes energy consumption, power quality and lighting comparisons for the LED and HPS lamps. Additional results are shown in Table 4, Table 5 and Table 6.

Table 3 - Energy Consumption, Power Quality and Lighting Comparisons

	LED		HPS		LED	HPS
	Photopic (fc)	Scotopic (fc)	Photopic (fc)	Scotopic (fc)	PAR (µE/m²)	PAR (µE/m²))
Avg Illuminance measured under usable area (standard = 30-100 fc)	139.28	369.68	222.13	441.69	142.57	143.83
Max	224.00	570.10	430.00	569.00	291.00	283.1
Min	35.70	105.00	129.00	97.80	39.04	57.53
Max/Min	6.27	5.43	3.33	5.82	7.45	4.92
Coefficient of Variation	0.47	0.43	0.16	0.31	0.53	0.37
Uniformity	3.90	3.52	1.72	4.52	3.52	2.50
Room Temperature	66		61			
Room Humidity	73%		77%			
Input Wattage	579		1041			
Power Factor	95.18		99.32			
Lighting Power Density (w/ft²)	4.02		7.22			

Table 4 – Summarized Energy Data from DENT Meter

Channel	Descrip.	Total Hours ON	Total Hours OFF	Total Hours	% ON	Max-kW[a] per room	Min-kW per room	Avg. kW[b] per room
1	HPS Lighting	4577	1513	6,090	75%	4.164	-	3.975
2	LED Lighting	4577	1513	6,090	75%	2.316	-	2.243
3	LED HVAC System	6090	0	6,090	100%	0.202	0.09	0.250
4	HPS HVAC System	6090	0	6,090	100%	0.212	0.10	0.246

a. Maximum kW occurs when system first powers on.
b. Average kW is the mean over the entire "on" period.
c. Installation occurred on 3/23/2014; lights on at 3/24/2014 6:00 AM.
d. Monitoring started 3/24/2014, 12:00:00 AM and stopped 3/11/2015 11:59:50 PM, for 352 days total. However, during March 2014 and June 2014, failures in the HPS system (two HPS lamps and one ballast) resulted in unreliable data during this period. The results shown in Table 4 are therefore based on the period of monitoring from July 1, 2014 through March 11, 2015.
e. The monitoring interval was 15 minutes.

Table 5 - Validated Power Factor and Energy Costs

Channel	Descrip.	PF	Fix /Room	Max W[a] /Fixture	Avg. W[b] /Fixture	Total[c] kWh/Rm	$/kWh	Cost /"on" hr./Fixture
1	HPS Lighting	99.32%	4	1041	993.648	18,190.72	0.108	$ 0.107
2	LED Lighting	95.18%	4	579	560.869	10,267.83	0.108	$ 0.061
3	LED HVAC	0.00%	1	295	249.799	1,521.34	0.108	$ 0.027
4	HPS HVAC	0.00%	1	309	246.058	1,498.55	0.108	$ 0.027

a. Maximum wattage occurs when system powers on.
b. Average wattage is the mean wattage over the entire "on" period, and is the wattage used for all calculations throughout this report.
c. Total kWh per room is calculated based on monitored data from two of the four HPS fixtures and two of the four LED lamps in each room; these measured values were then doubled to obtain the room total. (Excessive power draw of the HPS lighting limited monitoring to only two of the fixture/lamp types in each room.)

Table 6 – Published Versus Actual Energy Consumed

Lighting System	Published Specifications	Validated Wattage	% Actual
LED	650 watts	579	89%
HPS	1,000 watts	1041	101%

Total harmonic distortion and power factor from both the LED and HPS lighting systems were validated as shown in Table 7.

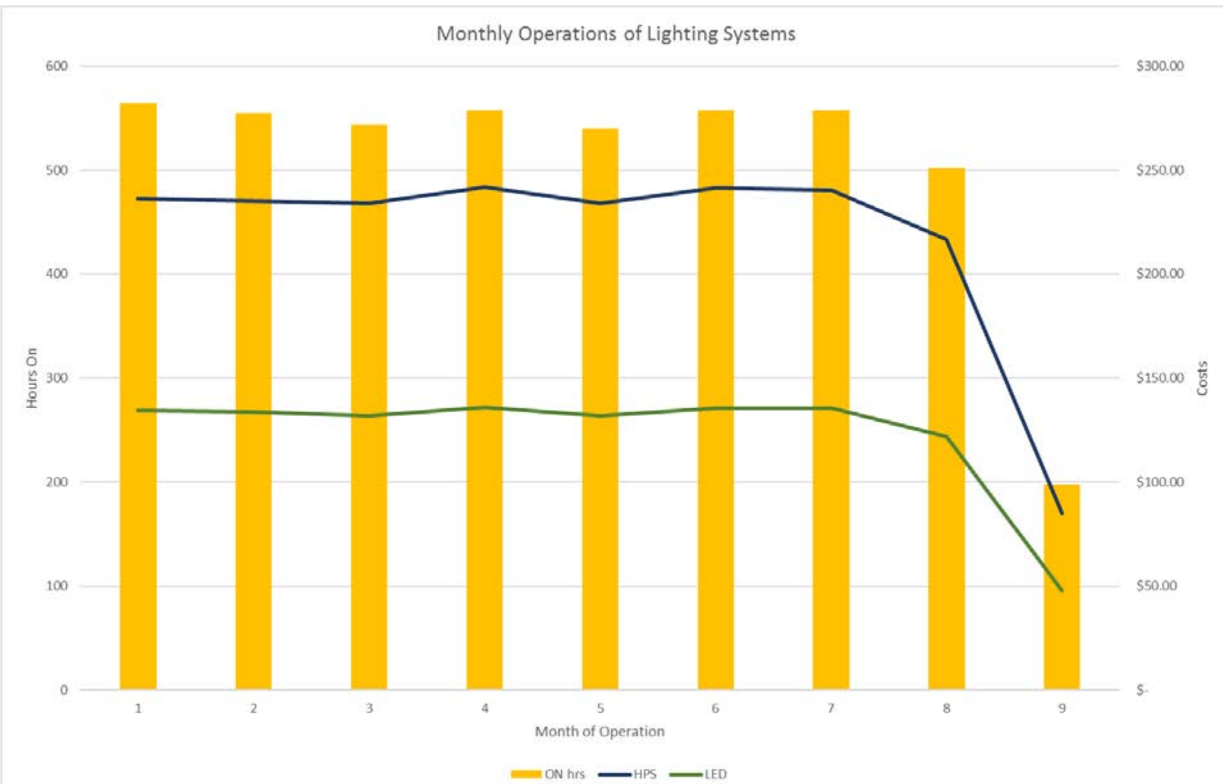
Table 7 - Validated Power Quality

Lighting System	Power Factor	3rd Harmonics	5th Harmonics
LED	99.27%	14.2%	3.0%
HPS	95.11%	21.8%	6.0%

The measured differences in total energy consumption and BTUs between the two propagation areas relative to heaters and blowing fans that operated during the three growth cycles is negligible.

Based on validated kWh usage, the energy costs to operate one HPS fixture was $0.107 per hour whereas the cost to operate one LED fixture was $0.061 per hour. Figure 17 outlines the monthly cost differential of the two lighting systems based on captured energy savings.

Figure 17 - Monthly Cost of Energy LED versus HPS



These findings have a projected annual cost savings of $886.38 or $17.73 per square foot using a rate of $0.108/kWh when propagating plants using LEDs versus conventional HPS installed in a controlled crop environment. This has been calculated using 4741 hours of “on” operations per calendar year, which provided a cost of $2,035.10 for HPS lighting and $1,148.72 for LED lighting.

Crop Outcomes

The project team examined three, 12-week growth cycles of plants under the two different light treatments to characterize outcomes as follows:

- Morphological (growth response)
- Photosynthetic response (instantaneous measure of photosynthetic rate of plants *in situ*)
- Photosynthetic response of plants to incremental increases in light (light response) and in carbon dioxide (CO2 response)

Four plants of each species were measured within each cycle and twice per plant, at 2 weeks and at 4 weeks after being moved in to the light environments. Morphological measurements taken on the four plants were height, leaf size, and leaf number. The photosynthetic rate, PAR level and leaf temperature of the four plants was also measured at the location of the plant in the enclosure[9] using a LiCor6400XT photosynthesis meter with a clear top on the leaf chamber that let in the ambient light at plant location.

Note: photosynthetic measurements are very dependent on light levels, which varied highly across the enclosure, and so were taken exactly where each plant sat.

In addition, for each cycle, four light and four CO2 response curves were developed using representative plants for each species. The leaf chamber used to derive these curves had an internal light source that could be adjusted for light intensity, as well as the capacity to alter the level of CO2 received by the leaf being measured. The light curves were developed by increasing PAR from 0 to 1000 (µmol photons $m^{-2}s^{-1}$) in increments of 100 units, while holding CO2 constant at 400 ppm CO2 per mole of air (this approximates ambient CO2). The CO2 response curves were developed using the same cuvette, but holding light constant at the average light level in the enclosures (140 µmol photons $m^{-2}s^{-1}$ for cycles 1 and 2 and 200 µmol $m^{-2}s^{-1}$for cycle 3) and increasing CO2 from 0 to 1000 at 100 unit increments.

The rationale for including the light and CO2 responses in the study was to help growers determine how much additional growth they could get by increasing light intensity in their operations or by injecting CO2 into their growing areas, and to see if the potential increase in growth from this supplementation was the same in HPS and LED environments or if it differed.

A more detailed summary of plant responses from Cycles 1, 2 and 3 is included in Appendix B.

Researchers from the Department of Horticulture Science at the University of Minnesota established identical soil, fertilizer and watering procedures, outlined in Table 8, that were monitored throughout the three growing cycles.

[9] Note: photosynthetic measurements are very dependent on light levels, which varied highly across the enclosure, and so were taken exactly where each plant sat.

Table 8 - Plant Propagation Environment

Item	Description
Soil Type	Sphagnum Peat/Composted Pine Bark/Perlite - Plaisted GH Mix
PH of Soil	5.9-6.2
Water Type	Well, incoming pH 6.7 adjusted with 93% H2SO4 (Sulfuric Acid) to 5.8
Chemical make-up of water: same tap, same container, etc.	All plants watered as needed with water indicated above
Explain in detail how you will measure the water per plant	All plants watered as needed. Net water used was monitored for each chamber, each cycle
Explain in detail how you will measure and administer fertilization or any other types of treatments	Fertilizer was given as a constant liquid feed at a rate of 50-100ppm N

Outcomes in Cycle 1, Cycle 2 and Cycle 3 in Table 9 showed some evidence of plant response by light source and amount of PAR reaching the plants. The response was mostly in morphology and growth, manifesting as larger/wider leaves or taller plants under HPS fixtures.

Table 9 - Growth, Light and CO_2 Response

Response Type	Description of Response
Morphologic Response (Cycle 1, 2 and 3)	HPS suggested a slight measured impact on plant height, leaf number and width of leaves overall for all species compared to LED. Cucumber plants grew faster and were larger under HPS for all measures and for all cycles.
Photosynthetic Response: Instantaneous (Cycle 1, 2 and 3)	Once the differences due to variable light levels and leaf temperatures across the enclosures was taken into account there was no difference between photosynthetic rates of plants grown under HPS and LED, with the exception of Basil. Basil also showed no differences in Cycles 1 and 2, but the plants under the HPS lights had a higher average photosynthetic rate in Cycle 3 that was not due to either leaf temperature or difference in PAR.

Response Type	Description of Response
Photosynthetic Response: A) Light (Cycle 1, 2 and 3)	Light response curves for all plants under HPS and LED were not significantly different at low light levels (<400 micromol) for any species. At higher light levels the curves sometimes diverged from one another, with the photosynthetic rates of LED grown plants exceeding those of HPS. This divergence, however, was inconsistent from cycle to cycle for lettuce and cucumbers. For Swiss chard, photosynthetic rates at high light levels were greater for plants under LEDs, but this difference disappeared in Cycle 3. Basil, in contrast, showed no difference in light response curves between LED and HPS plants in cycles 1 and 2, but in Cycle 3 the HPS plants had higher photosynthetic rates at light levels of 400 micromols or higher.
B) CO_2	Responses of plant photosynthetic rates to increasing CO_2 levels followed a similar pattern to the light curves. Photosynthetic rates only diverged at high CO_2 concentrations (>400 ppm) and did not do so consistently from cycle to cycle for lettuce and Swiss chard. Cucumbers did not show any differences between LED and HPS curves for any cycle. Basil did not differ between LED and HPS for cycles 1 and 2, but did have higher photosynthetic rates under the HPS lights than under the LED lights at higher light levels.

In Cycle 3, the project team moved plant trays one foot closer to the light source to examine changes in leaf anatomy resulting from plants receiving higher PAR. HPS plants were taller and produced wider leaves for all species and looked different than crops grown under LEDs.

Although slightly different plant impacts were identified, none of the research suggested negative outcomes from growing under LED lighting. In fact, the study identified new areas of plant research as LED crops in Cycle 3 showed evidence of more compact growth and smaller but more vibrantly colored leaves, and possibly a stronger root base when positioned closer to the plants.

These findings warrant continued field study to better understand plant morphology, nutritional characteristics or disease prevention that could be realized from the LED lighting system positioned to optimize growth.

As demonstrated earlier in Figures 13 and 14, measured HPS and LED PAR **distribution varied a great deal across the test cells.** Those variances produced larger standard errors meaning fewer significant differences detected in Cycles 1 and 2 no matter what light source was applied.

In Cycle 3, basil had the most significant photosynthetic response to higher PAR and higher CO2 levels. Outcomes from Cycle 3 showed how increased PAR affected a growth response that warranted more study.

This demonstration suggested opportunities to explore and develop recommendations for a "secret sauce" or special light recipe tailored to crops grown and placement of LEDs (see Appendix B – Light Response Curves Figures 23-26) because some crops required more PAR than others.

It was challenging to suggest one light source as superior over the other as pertains to a better plant response with a high level of confidence because light intensity directed at individual plants varied widely over the experimental plant trays in this demonstration.

In conclusion, light levels varied a great deal across each enclosure. Photosynthesis is directly related to light levels so those plants getting more light, regardless of light source (HPS or LED) generally had higher photosynthetic rates. This variability was compounded when Cycle 3 plants were moved closer to the light source. [10]

Figure 18 and Figure 19 demonstrate that even though Cycle 3 plants grown under HPS were taller and produced wider leaves, these were outcomes likely created by a temperature effect from the forward heat produced by HPS that did not occur under LEDs. [11]

Figure 18 – Cycle 3 Lettuce Grown under HPS (left) versus LEDs (right) – Leaf Growth

[10] Email message from U of Minnesota plant researcher E. Gesick, to authors, July 2, 2015.

[11] Ibid.

Figure 19 – Cycle 3 Lettuce Grown under HPS (left) versus LEDs (right)

The plants grown under LED fixtures appeared deeper in color, had more compact growth and showed some evidence of a slightly stronger rooting system. These findings could be the foundation for more healthy, less disease prone plants with richer vitamin content.

Similar observations were made for Swiss chard and basil plants (Figure 20 and Figure 21). Both showed visual differences in plant size between crops grown under HPS versus LED fixtures that were not fully explained by this research. Although larger in size and taller with wider leaves, the plants grown under HPS fixtures had elongated stems, more yellowing leaves and the rooting system appeared a little less developed compared to the experimental plants propagated under red and blue LEDs.

Figure 20 – Cycle 3 Swiss Chard Grown under HPS (left) versus LEDs (right)

Figure 21 - Cycle 3 Basil Grown under HPS (left) versus LEDs (right)

One caveat regarding this comparison is the fact that the plants under the HPS lamps were well past their harvest stage when data was collected at 4 weeks, the interval we had used for cycles 1 and 2, whereas the LED plants had just reached harvest stage.[12] A better comparison of crop quality might be between plants in the two environments at harvest stage rather than a set number of weeks.

These observations and varied visible growth outcomes from Cycle 3 warranted further study in PAR intensity.

Research implications pertaining to plants from Cycle 3 are as follows:

1. Moving plants closer to the light source produced intriguing outcomes by crop species. Indications are that plants produced under LED fixtures may be higher quality, more compact and possibly more nutritionally dense compared with plants grown under HPS lighting.
2. Crop response to narrow spectrum lighting from LEDs was observed in this study.
3. Cycle 3 outcomes showed notable growth differences between HPS and LED light on experimental plants. Plant responses to more heat from HPS (left) and red and blue light from LED (right) were clearly noticeable (Figure 19, Figure 20 and Figure 21).

[12] We had no idea what the effects of changing from HPS to LED lamps would be, so there was no reason to change the protocols we had set up for the experiment in terms of when data was collected. We wanted to keep the intervals of measurement the same across all cycles. However, the heat from the HPS lamps pushed the plants in that environment much faster than happened under the LEDs. As a result, the plants under the HPS reached harvest stage two weeks ahead of those under LEDs for cycle 3, and they continued to increase in size until the four week measurements were taken.

Financial Projections & Implications

An important issue for LEDs versus HPS lighting in horticulture applications is economic viability, especially as the cost of SSL technology declines. Despite their higher first cost, an investment in LED fixtures could support year-round crop production and demonstrated a good return on investment in this research project.

When sole source lighting was used to propagate crops, LED fixtures in this study were the clear winner by operating at much lower energy cost to give the same plant response.

Financial projections over a twenty year horizon make the case for LED fixtures. The total cost for an LED lighting system is projected at $52,909 versus a total cost of $76,406 for an HPS system. Although maintenance cost savings was a benefit, the primary driver was over $29,343 in energy savings that would be realized to the crop grower if they deployed LEDs for this application.

It should be noted that the study detected uneven light distribution from LED fixtures. Careful financial consideration must be determined by crop species because some plants may necessitate more intense or uniform light and that could drive up fixture costs.

Table 10 - Twenty-year Cost Projections

Financial Summary Comparison	LED	HPS
Total Cost over 20 year period	$54,060	$79,442
PV Cost @ 5%	$36,592	$51,673
Internal Rate of Return (IRR)		
Projected Payback --- years	89.8%	
	2.10	--

It is important to factor in the possibility that an investment in more LEDs may be necessary to hit higher PAR lighting requirements required to grow certain crops year-round, including basil.

This research suggests that the position of the light source relative to the crops might require a different light configuration by plant species. Growers will want to be careful not to over-invest in PAR light if it is not needed. It might be necessary for each LED manufacturer to develop a light recipe by crop.

Key assumptions to 20-year Net Present Value calculations (Table 11 and Table 12) include:

- Fixture Unit Cost of $1,099 for LED, $280 for HPS
- Purchase of 4 fixtures each: LED total cost $4,396; HPS $1,120
- Two HPS bulb and ballast failures and replacement (based on experience in this project)
- One-year warranty on HPS bulb; five-year warranty on LED and driver
- 50,000 rated life of LED versus 24,000 rated life of HPS
- Photoperiod of 18 hours a day
- Labor Rate of $100/hour; 1 hour of labor for each fixture installation
- Cost of capital 5%; Discount rate 5%; Inflation rate 2%
- Electric utility rate $/kwh .108

Table 11 - Net Present Value of LED

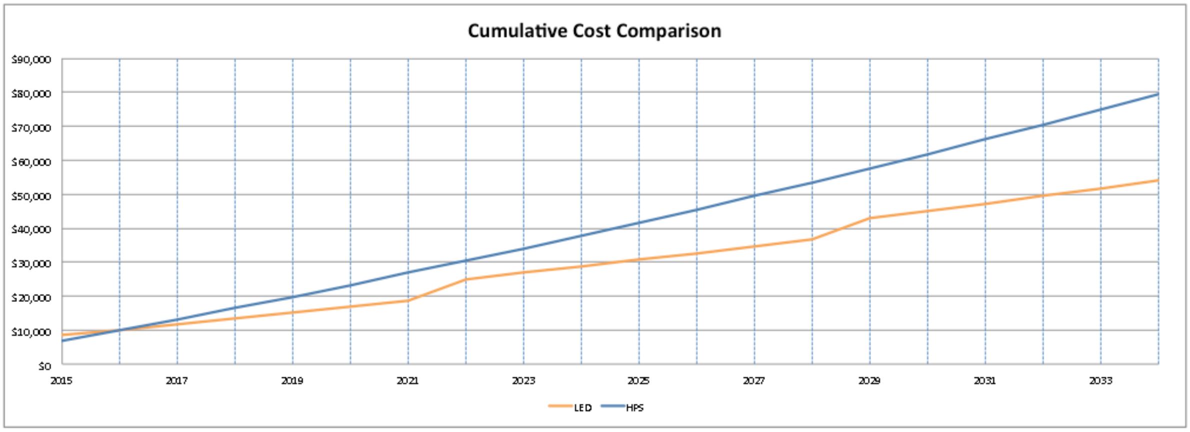
20 Year Financial Analysis - LED					
EOY	Energy Cost	Light System	Installation	Total Costs	Cummulative Costs
2015	$1,580.90	$4,396.00	$2,500.00	$8,476.90	$8,476.90
2016	$1,612.52	$0.00	$0.00	$1,612.52	$10,089.42
2017	$1,644.77	$0.00	$0.00	$1,644.77	$11,734.19
2018	$1,677.66	$0.00	$0.00	$1,677.66	$13,411.85
2019	$1,711.22	$0.00	$0.00	$1,711.22	$15,123.07
2020	$1,745.44	$0.00	$0.00	$1,745.44	$16,868.51
2021	$1,780.35			$1,780.35	$18,648.86
2022	$1,815.96	$4,088.28	$441.63	$6,345.87	$24,994.73
2023	$1,852.28			$1,852.28	$26,847.00
2024	$1,889.32			$1,889.32	$28,736.32
2025	$1,927.11	$0.00	$0.00	$1,927.11	$30,663.43
2026	$1,965.65			$1,965.65	$32,629.08
2027	$2,004.96			$2,004.96	$34,634.04
2028	$2,045.06			$2,045.06	$36,679.11
2029	$2,085.96	$3,780.56	$441.63	$6,308.16	$42,987.26
2030	$2,127.68			$2,127.68	$45,114.94
2031	$2,170.24			$2,170.24	$47,285.18
2032	$2,213.64			$2,213.64	$49,498.82
2033	$2,257.91			$2,257.91	$51,756.74
2034	$2,303.07			$2,303.07	$54,059.81
Totals	**$38,411.70**	**$12,264.84**	**$3,383.26**	**$54,059.81**	

Table 12 - Net Present Value of HPS

20 Year Financial Analysis - HPS									
EOY	Energy Cost	Light System	Installation	Light Bulb Replacement	Light Bulb Replacement Install	Driver/Ballast Replacement	Driver/Ballast Replacement Install	Total Costs	Cummulative Costs
2015	$2,788.57	$1,120.00	$2,500.00	$100.00	$50.00	$132.00	$50.00	$6,740.57	$6,740.57
2016	$2,844.34	$0.00	$0.00	$102.00	$51.00	$134.64	$51.00	$3,182.98	$9,923.55
2017	$2,901.23	$0.00	$0.00	$104.04	$52.02	$137.33	$52.02	$3,246.64	$13,170.19
2018	$2,959.25	$0.00	$0.00	$106.12	$53.06	$140.08	$53.06	$3,311.57	$16,481.77
2019	$3,018.44	$0.00	$0.00	$108.24	$54.12	$142.88	$54.12	$3,377.81	$19,859.58
2020	$3,078.81	$0.00	$0.00	$110.41	$55.20	$145.74	$55.20	$3,445.36	$23,304.94
2021	$3,140.38	$0.00	$0.00	$112.62	$56.31	$148.65	$56.31	$3,514.27	$26,819.21
2022	$3,203.19	$0.00	$0.00	$114.87	$57.43	$151.63	$57.43	$3,584.55	$30,403.76
2023	$3,267.26	$0.00	$0.00	$117.17	$58.58	$154.66	$58.58	$3,656.25	$34,060.01
2024	$3,332.60	$0.00	$0.00	$119.51	$59.75	$157.75	$59.75	$3,729.37	$37,789.38
2025	$3,399.25	$0.00	$0.00	$121.90	$60.95	$160.91	$60.95	$3,803.96	$41,593.34
2026	$3,467.24	$0.00	$0.00	$124.34	$62.17	$164.13	$62.17	$3,880.04	$45,473.38
2027	$3,536.58	$0.00	$0.00	$126.82	$63.41	$167.41	$63.41	$3,957.64	$49,431.01
2028	$3,607.31	$0.00	$0.00	$129.36	$64.68	$170.76	$64.68	$4,036.79	$53,467.80
2029	$3,679.46	$0.00	$0.00	$131.95	$65.97	$174.17	$65.97	$4,117.53	$57,585.33
2030	$3,753.05	$0.00	$0.00	$134.59	$67.29	$177.65	$67.29	$4,199.88	$61,785.21
2031	$3,828.11	$0.00	$0.00	$137.28	$68.64	$181.21	$68.64	$4,283.87	$66,069.08
2032	$3,904.67	$0.00	$0.00	$140.02	$70.01	$184.83	$70.01	$4,369.55	$70,438.64
2033	$3,982.77	$0.00	$0.00	$142.82	$71.41	$188.53	$71.41	$4,456.94	$74,895.58
2034	$4,062.42	$0.00	$0.00	$145.68	$72.84	$192.30	$72.84	$4,546.08	$79,441.66
Totals	**$67,754.94**	**$1,120.00**	**$2,500.00**	**$2,429.74**	**$1,214.87**	**$3,207.25**	**$1,214.87**	**$79,441.66**	

Cumulative financial projections in Figure 22 indicated that an investment in LED lighting for controlled production environments would be expected to be the least cost lighting solution compared to HPS for controlled environment agriculture.

Figure 22: Cumulative Lighting System Control Comparison



Research Conclusions & Recommendations

This research made it possible to develop an initial approach to installing LED lighting and determining the energy savings realized. The outcomes demonstrated that it was possible to produce plants under 100% LEDs that met our criteria of no negative impacts to the plants, while achieving substantial energy saving.

This project confirmed that LED fixtures are a more reliable, energy-efficient light source. Compared with HPS fixtures, which emit more heat than LED fixtures, LED fixtures can be brought much closer to plant tissues. To optimize growth, LED fixtures may benefit only those seedlings that are placed directly below the light source. Consequently, more LED fixtures might be required to achieve better optics for some plants to hit higher PAR requirements that will optimize crop production.

If energy and maintenance savings are the goal in controlled environment crops, this research suggested LED fixtures were more cost effective compared to HPS fixtures. These results will give rise to other light and plant research before HPS fixtures in cultivation rooms are completely replaced with LED fixtures when plant response is the primary driver.

Other findings left questions about energy efficiency tradeoffs with PAR across an entire greenhouse under LEDs. Although this study revealed unchartered waters relative to crop responses, these findings might help begin to guide mounting LEDs and fixture positioning for a variety of purposes depending on crop type and desired growth outcomes.

This research confirmed that light location and uniformity can have an effect of crop productivity and a one-size approach cannot be taken with LEDs.

The values measured in PAR light bode well for growing some plants under LED fixtures. There were small variations in plant growth between plants grown under LED and HSP fixtures until plants were moved closed to the light source. That change revealed further areas of exciting new research opportunities related to plant health under LED lighting.

Solid-state lighting is improving at a rapid pace. Ideally LED manufacturers will provide standard ranges for LED modules and tunable drivers that change light spectrum or controls based on different crops. Few manufacturers have taken a serious look at other sustainability issues including recyclability and disposal of LED fixtures yet.

Based on these findings from this technology demonstration, the project team makes the following recommendations:

1. Utilities should include the specialized LED fixtures in their Conservation Improvement Program (CIP) offerings to customers with commercial crop growing operations. The LED fixture model in this study performed better than specifications and met several key quality standards including power factor and harmonics that were comparable to HPS.
2. Growers and LED lighting manufactures should consider developing LED lighting specifications for commercial crop growers, similar to DesignLight Consortium qualified products. Outcomes in this project demonstrated confidence in LED fixture reliability, however that does imply that all LED fixtures will perform the same. LED lighting products vary greatly.

3. Growers should consider new questions raised by this project regarding LED lighting for controlled environment agriculture including the following:
    a. What proportion of red and blue light is required to optimize crops?
    b. What is the ideal spectral light intensity by crop?
    c. Could other growth (morphologic) and light (photosynthesis) responses from LEDs contribute to disease resistance or healthier overall crop production?
4. Growers should include appropriate auxiliary lighting that provides white light in a controlled environment. This research demonstrated the difficulty for employees to see under blue and red wavelengths required by plants versus lumens or foot candles required for vision by employees.
5. Growers should follow manufacturer guidelines when installing LED lighting systems by crop species if available. Published recommended LED illumination and PAR guidelines will prevent crop growers from wasting energy and lumens to produce more light than may be necessary to optimize plant growth.
6. The controlled environment agriculture industry should build on these findings to develop recommended best practices on configuring LED fixtures in high-tunnel crop production. Recommended outcomes should optimize both energy efficiency and plant production by crop species. Although no negative plant outcomes were identified from growing crops under LEDs, this project demonstrated variability in PAR light that may be cost-effective for growing some plants, but not for others.
7. Growers should build on this research by forecasting profit margins to be realized by crops to assess the cost/benefit analysis for growers setting up growing environments using LED equipment year-round as a new business opportunity to accommodate the regional farm-to-table movement in Minnesota.
8. Growers, utilities, and regulators should be aware of other LED systems recently on the market. These systems are designed for controlled crop production that places light within inches of the canopy including orbital gardens by Garden Fresh Farms (http://www.gardenfreshfarms.com/) or Freight Farms leafy green machine (http://www.freightfarms.com/).

References

Cornell University Controlled Environment Agriculture (CEA) Program 2014

Dorias, M., "Use of Supplemental Lighting for Vegetable Crop Production: Light Intensity, Crop Response, Nutrition, Crop Management, Cultural Practices," Canadian Greenhouse Conference, October 9, 2003.

Gesick, E., July 2, 2015. Email message from U of Minnesota plant researcher to authors.

Jianzhond, Jiao , PhD, The Latest in LED Test Methods & Standards, Osram Opto Semiconductors

Lighting Systems for Agriculture Facilities, American Society of Agriculture & Biological Engineers (ASAE) EP344.3, Jan 2005

Massa, et al., "Plant Productivity in Response to LED Lighting," HortScience, December 2008, Vol .43, no 7. p 1951-1956

Sabzalian, et al., "High Performance of Vegetables and Flowers and Medicinal Plants in Red/Blue LED Incubators for Indoor Plant Production," Agronomy for Sustainable Development, October 2014, Vol. 34, Issue 4, pp. 879-886

Appendix A

Figure 23 - LumiGrow Product Specifications

LumiGrow Pro Series™ LED Lighting Systems

Gain Unprecedented Power and Control with LumiGrow Pro

Well-designed lighting systems boost yield and quality. But ordinary lights cost so much to operate that they erode profits. With the LumiGrow Pro series, you no longer need to choose between boosting yields and controlling costs. LumiGrow Pro lights delivers both benefits with the industry's two most powerful LED fixtures for greenhouses: the LumiGrow Pro 325™ and the LumiGrow Pro 650™. It's no wonder LumiGrow is the choice of 1,000+ growers from Alaska to Australia.

Improve Crop Yield and Uniformity

You'll make the most of your greenhouse or other growing environment because the LumiGrow Pro series provides uniform light distribution without harmful hot spots. In addition, LumiGrow lights run 70% cooler than high-intensity discharge (HID) lights, eliminating plant damage and problems related to unmanaged greenhouse temperatures. Hot-running HID lights stress plants as evidenced by high water and nutrient demand. By contrast, plants grow safely at any distance from LumiGrow lights.

Reduce Your Operating Costs

Energy-efficient LumiGrow Pro series lights cost between 40% to 70% less to operate compared to HID lamps. New sites see dramatically lower infrastructure costs because of reduced electrical requirements. LumiGrow lights also eliminate the need for ballasts and reflectors while they minimize cooling loads, accelerating your payback. Growers see electrical bills trimmed by approximately half, month after month, year after year.

How It Works

The Pro series equips growers with LED lights that output more red and blue in the essential PAR range than the industry's most powerful conventional systems, including any high-intensity discharge (HID) fixture. Peerless in the industry, Pro 325 and Pro 650 lights double and quadruple, respectively, the brightness and efficiency of the LumiGrow ES330™ system, previously the industry's most powerful LED light.

LumiGrow Pro 325 Horticultural Light

The Pro 325 system is engineered for commercial greenhouses and controlled environment agriculture (CEA) environments. Like all LumiGrow solutions, the Pro 325 light eliminates waste inherent to HID lights by focusing photons in plants' primary response regions rather than in spectral regions plants can't use. All of the light produced by the Pro 325 system is productive for plants, yielding 70% energy savings versus the 1000-Watt HID lights they replace.

LumiGrow Pro 650 Horticultural Light

The Pro 650 system raises the PAR bar for the entire horticultural lighting industry. The Pro 650 light is for growers and scientists who require red and blue PAR output greater than that of 1000-Watt HID lights without the costly energy demand of these fixtures. Energy savings versus a 1000-Watt HID light is approximately 40%.

Applications

- Commercial Greenhouses
- Nurseries
- Indoor and Vertical Farms
- Research

Start the switch. Apply to the Fall 2012 Pilot Program.
Contact **LumiGrow (800) 514-0487 www.lumigrow.com**

LumiGrow Pro Series

The leader in smart horticultural lighting.

Key Features

Provides Maximum Light Density
- Enhanced spectral output covering full PAR
- More red and blue PAR per Watt than any other lighting fixture
- Industry's most efficient LEDs
- Small hardware footprint minimizes plant canopy shadowing

Puts Control at Your Fingertips
- Individually adjustable 3-channel (red, blue and white) knobs for precise spectral control
- White-only View mode
- Compatible with automated control systems

Delivers Advanced Thermal Management
- Runs 70% cooler than HID lighting
- Massive heat sinks keep LEDs running cool
- Operates safely without high voltage

Reduces Your Costs with Energy Efficiency
- Pro 325 uses approximately 70% less energy than the equivalent 1000-Watt HID light and Pro 650 uses 40% less energy
- Eligible for energy utility rebates

Make the Environmentally Responsible Choice
- RoHS compliant (mercury- and lead-free)
- Long lasting

Installs and Operates Simply
- Smart Volt auto-switching and regulating power supply adjusts to appropriate voltage for international use
- Installs just like HID lights and operates seamlessly alongside them

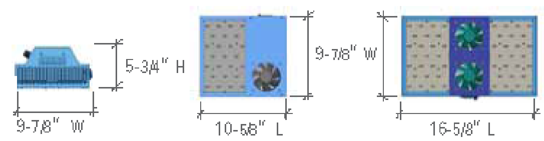
Built to Last
- Light-weight, yet strong powder-coated aluminum hardware
- Proprietary constant-current LED controllers
- 5-year warranty
- Customer Support from a US-based manufacturer

LumiGrow SmartPAR™ Software Compatible
- Boost productivity even further when you operate the lights with SmartPAR, the industry's first greenhouse light management software. Ask your LumiGrow representative for details.

Contact LumiGrow
(800) 514-0487
www.lumigrow.com

Pro Series Technical Specifications

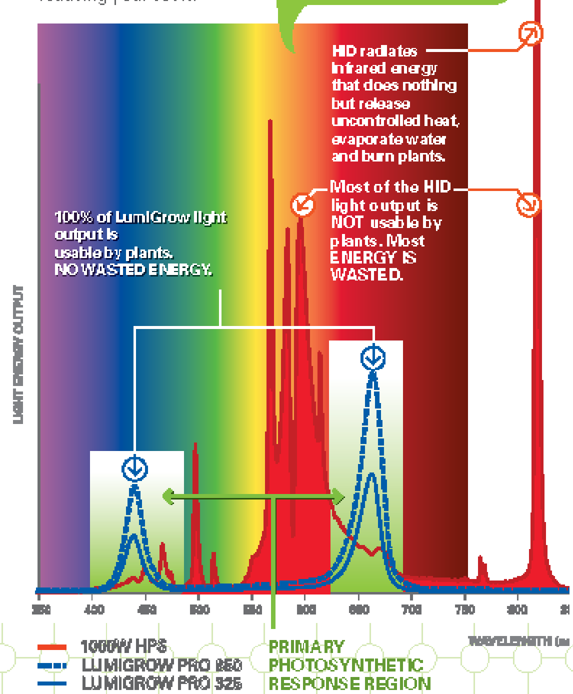
Energy Consumption	325 Watts	650 Watts
Operating Voltage	100-120/200-240 V_{ac} (5A/2.5A max) (auto-switching)	100-240 V_{ac} (8.5A/5A max) (auto-switching)
Dimensions	9-7/8" W x 10-5/8" L x 5-3/4" H	9-7/8" W x 16-5/8" L x 5-3/4" H
Weight	9 lbs	16 lbs
Operating Frequency	50Hz/60Hz	
Operating Temperature	– 4º F to 140º F (– 20º C to 60º C)	
Lifespan	50,000 hours	



Targeted Spectral Output

All light emitted by the LumiGrow Pro light triggers healthy plant responses, boosting your yield and reducing your costs.

Excess light from HIDs costs you in high electrical bills.



Earth Worth Plantanator

Figure 24 – Earth Worth Product Specifications

What makes the Earth Worth Plantanator 1000w growing solution so special? Our innovative dual bulb system provides the best of both worlds. You simply use the 1000W High Pressure Sodium (HPS) as your starter bulb. It will accelerate seed/plant development, increase chlorophyll productions, and result in optimal flowering. Once your vegetative area starts getting a little larger, or when you are growing plants larger than 24 inches tall vegetatively, you simply toss in the metal halide (MH) bulb.

The **Earth Worth hood reflector system** incorporates a mirrored reflector and glass shield for optimal vegetative growth, venting, and bulb cooling. The large reflector area permits greater heat dissipation and is guaranteed to yield large crops.

Specifications & Features:

- 6" air vent works perfectly with our 6" exhaust fan system (NOT included)
- Large Tempered Glass Cover
- Extremely Heat Isolative
- Will support bulbs up to 1000 watts
- Overall Reflector Dimensions: 19-1/2in.(L)x 6in.(Diameter)
- Interior Reflective Sheet Dimensions: 19in.(L) x 9in.(W)
- Reflector Dimensions: 26in.(L) x 22-1/4in.(W) x 10in.(H)

EW-1000MH Metal Halide bulbs:

The EW-1000MH bulbs are designed to grow healthy, high producing plants across each phase of their growth cycle.

Specifications:

- Power: 1000 watts (High efficiency)
- Rated Life: 10,000 hours
- Lumens: 60,000
- Color Temperature: 4,200K
- Contains bluer spectrum, which is best for vegetation.
- High output, high luminescence efficiency.

EW-1000HPS High Pressure Sodium bulbs:

The EW-1000HPS bulbs are designed to grow healthy, high producing plants across each phase of their growth cycle.

Specifications:

- Power: 1000 watts (High efficiency)
- Rated Life: 24,000 hours
- Lumens: 90,000
- Contains redder spectrum light, which is best for flowering.
- Color Temperature: 2,100K
- High output, high luminescence efficiency.

EW-1000S Ballast:

Our ballasts were specifically designed to grow healthy, high producing plants across each phase of their growth cycle. The EW-1000S Swichable Ballast is constructed of the highest quality electronics to exacting quality control standards to ensure you years of trouble free service. Our high performance ballasts are electronically optimized for growers who use both High Pressure Sodium (HPS) bulbs and Metal Halide (MH) Bulbs 1000 Watt Grow Light Systems.

Specifications:

- Rated Power: 1000 watts (High efficiency)
- Switchable Between HPS and MH Bulbs
- Bulb Compatibility: 1000 watts High Pressure Sodium Lamps OR Metal Halide Lamps
- Provides Cleaner & Constant Power to Bulbs, Maximizing Life and Crop Yield
- Components are shielded to protect against R.F.I.(Radio Frequency Interference)
- Working Voltage - 120/240
- FCC/CE Certified
- Energy saving and environmental friendly
- Specified Frequency: 50/60Hz
- Size: 13-1/2in. x 8in. x 8-1/2in.
- Power Cord: 8-1/3ft. 3 Prong Power Cord (US standard plug)

Electronic Grow Timer:

Our timer was designed for hydroponic gardeners to control the accurate timing of lighting system or odor scrubbing systems for plants. Now you will never need to worry about turning lights on or off.

Specifications:

- Safe and simple to use
- Once activated, the timer will start/stop your appliance or lighting as required.
- The timer can be easily overridden.
- Timer Power: Max Wattage 1725W; Max Current 15A/120V/60Hz

Kit includes 2 free locking Yo-Yo adjustable light hangers.

Appendix B

NOTE: Copies of detailed findings, power point slides with tables and graphs with data points from Cycles 1, 2 and 3 can be obtained by contacting Esther Gesick, University of Minnesota –gesic001@umn.edu.

CYCLE 1:

Growth (Morphological) Response

Swiss Chard and Lettuce grown in the HPS and LED treatments exhibited no significant differences in the morphological measures that were taken.

Basil was taller on average in the HPS treatment when height data was taken two weeks after transplant and also four weeks after transplant, and the height difference was statistically significant (p=0.05).

Cucumbers were larger in all measurements under HPS and differed significantly in all measurements except height taken two weeks after sowing. Height increased more in the HPS treatment than the LED treatment after four weeks and that change was significant. Leaf number was also higher at four weeks under HPS lighting and the change in leaf number was significant

Photosynthetic Response to Light:

The HPS and LED light response curves for Swiss Chard and for Lettuce differed significantly at p=0.05, but this difference was primarily because of divergence at high light levels. At the light levels in the enclosures, the differences in the light curves was not significant.

The HPS and LED light response curves for Basil and Cucumber did not differ significantly at any light levels.

Photosynthetic Response to CO_2:

The CO_2 response curves for the HPS and LED treatments for Swiss Chard diff ered significantly at p=0.05, but only at levels of CO_2 above 400 ppm per mol air did they diverge.

There was no significant diff erence between the HPS and LED responses to CO_2 for the other three species.

CYCLE 2:

Growth (Morphologic) Response

Swiss chard and Lettuce grown in the HPS and LED treatments exhibited no significant differences in the morphological measures that were taken.

Basil was had a slightly larger leaf width on average in the HPS treatment when data was taken four weeks after transplant, and the difference was statistically significant ($p=0.05$). There were no other significant differences in the growth of Basil.

Cucumbers were larger in all measurements under HPS, but the difference was significant ($p=0.05$) only for height four weeks after sowing. The change in height also increased more in the HPS treatment than the LED treatment after four weeks and that change was significant.

Photosynthetic Response to Light:

The HPS and LED light response curves for Swiss chard and for cucumber differed significantly at $p=0.05$, but this difference was primarily because of divergence at high light levels. At the light levels in the enclosures, the differences in the light curves were not significant.

The HPS and LED light response curves for basil and lettuce did not differ significantly at any light levels.

Photosynthetic Response to CO_2:

The CO_2 response curves for the HPS and LED treatments for Lettuce differed significantly at $p=0.05$, but only at levels of CO_2 between 200 and 600 ppm.

There was no significant difference between the HPS and LED responses to CO_2 for the other three species.

CYCLE 3:

Growth (Morphologic) Response:

Height and leaf number were significantly greater for all species under HPS at both 2 and 4 weeks after transplanting

Leaf width was significantly larger under HPS for Basil and Cucumber at 2 weeks after transplant and for Swiss Chard at 4 weeks after transplant.

The change in height between 2 weeks and 4 weeks was significantly greater under HPS for Basil and Cucumber.

The change in leaf number between 2 and 4 weeks was significantly larger under HPS for Swiss Chard.

Photosynthetic Response to Light:

The HPS and LED light response curves for Basil differed significantly at p=0.05 at all light levels.

The HPS and LED light response curves for the other three species did not differ significantly at any light levels.

Photosynthetic Response to CO_2:

The CO_2 response curves for the HPS and LED treatments for Basil differed significantly at p=0.05 at all CO_2 levels.

There was no significant difference between the HPS and LED responses to CO_2 for the other three species.

Figure 25 – Cycle 3 Light Response curve for Swiss Chard

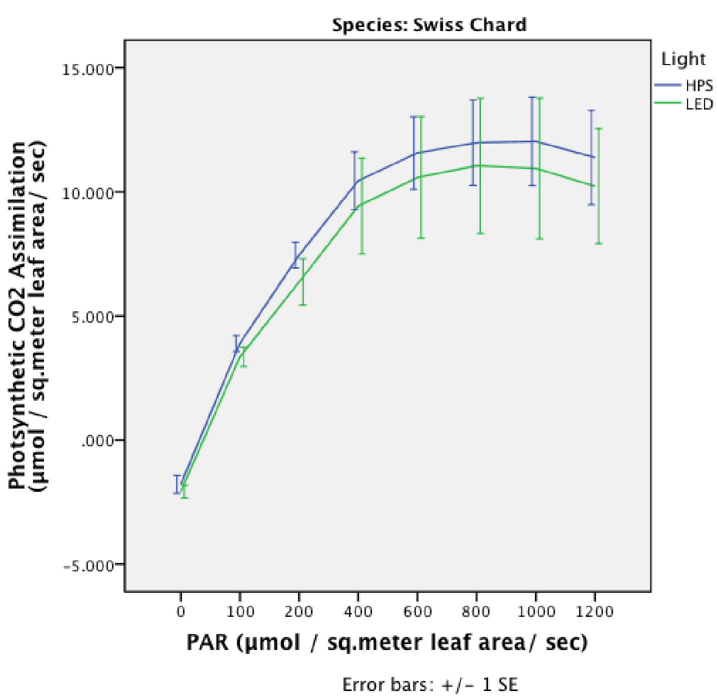


Figure 26 – Cycle 3 Light Response Curve for Lettuce

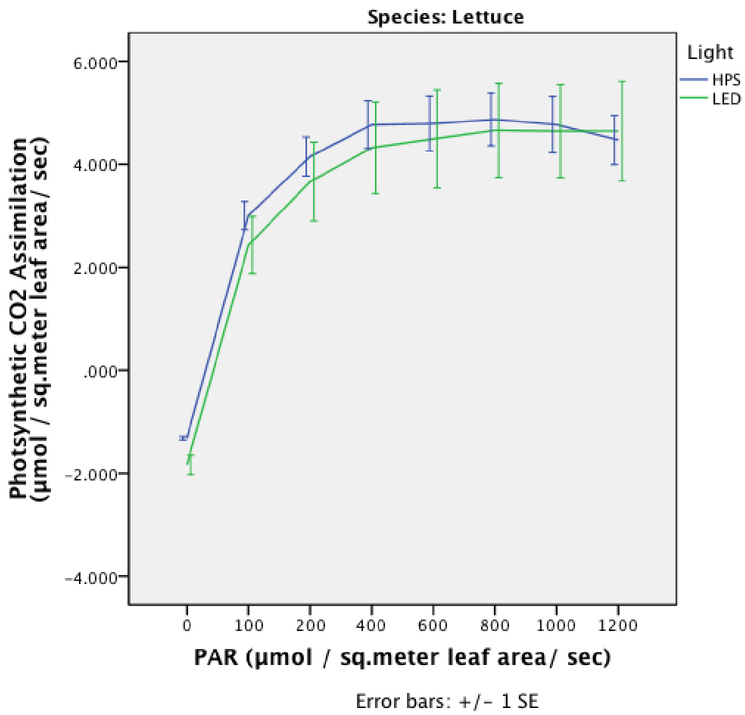


Figure 27 – Cycle 3 Light Response Curve for Basil

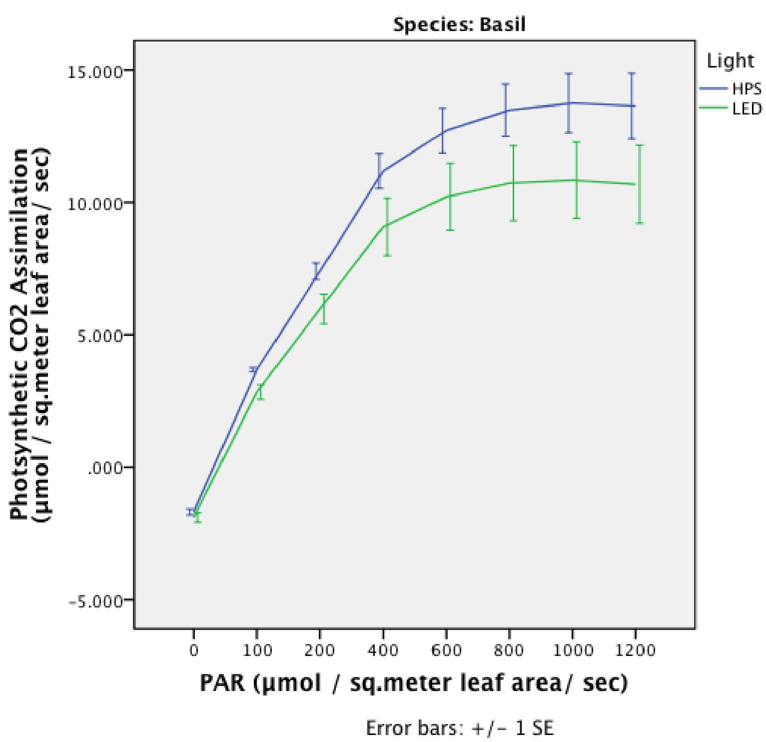


Figure 28 – Cycle 3 Light Response Curve for Cucumbers