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Solid-State Lighting Program and USDA-ARS: R&D Meeting

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Disclaimer

DOE Solid-State Lighting Program and USDA-ARS, "Horticultural Lighting Energy meeting" December 2021.

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Solid-State Lighting Program
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Authors:
Morgan Pattison, Solid State Lighting Advisors
Jennifer Boldt, USDA-Agricultural Research Service
Kyung Lee, Guidehouse, Inc.
Sean Donnelly, Guidehouse, Inc.

Comments

The Energy Department is interested in feedback or comments on the materials presented in this document. Please write to Wyatt Merrill, Solid-State Lighting Program Manager:

Wyatt Merrill, Ph.D.
Solid-State Lighting Program Manager
U.S. Department of Energy
1000 Independence Avenue SW
Washington, D.C. 20585-0121

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R&D Meeting Participants

Kyung Lee	Guidehouse
Kale Harbick	USDA ARS
Bruce Bugbee	Utah State University
Marc van Iersel	University of Georgia
David Bubenheim	Advisor to the University of California
Erik Runkle	Michigan State University
Tessa Pocock	Soli Organic
Roger Buelow	AeroFarms
Erico Mattos	GLASE Consortium
Kyle Booth	Energy Solutions
Jeff Lockner	UL
A.J. Both	Rutgers University
Stuart Berjansky	DesignLights Consortium
Derek Smith	Resource Innovation Institute
Thao Chau	California Energy Commission

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1 Introduction

On December 2, 2021, fifteen experts in fields related to horticultural lighting and associated energy consumption gathered at the invitation of the Department of Energy (DOE) Solid-State Lighting (SSL) Program and the United States Department of Agriculture (USDA) Agricultural Research Service (ARS). The meeting was held virtually. The objectives of the meetings were to:

1. highlight research and development opportunities within the topic of horticultural lighting,
2. bridge R&D efforts among horticultural scientists, lighting scientists, and energy managers,
3. facilitate collaboration; and
4. provide guidance to the DOE, USDA, and other R&D efforts on this topic

This topic is of interest to the US DOE SSL and USDA ARS Programs because light-emitting diode (LED) lighting technology provides the opportunity to not only reduce horticultural lighting energy consumption but also increase horticultural productivity and enable new elements of the horticultural supply chain, such as vertical farming. Improved lighting enabled by LED technology can decrease the energy required for plant production and improve productivity and/or plant quality. However, the understanding of plant physiological responses to light is still evolving and optimized practices are still being developed. As this understanding evolves, consistent lighting product characterization standards and practices need to be developed. In addition, the energy implications of controlled environments for different crops and different production settings must be better understood.

This report summarizes the R&D themes and the discussions. Overviews of the participants' presentations and related remarks are included in Appendix A of the report.

2 Key Themes

The meeting format encouraged each of the attendees to participate and present findings from their own activities. The discussions following the presentations offered the opportunity to review details from the presentations. There were some research areas that were consistently mentioned as potential topics for advancing understanding. These discussion themes are listed here:

- Energy Consumption and Reporting
- Lighting Product Performance and Characterization
- Yield and Plant Physiological Responses to Light

2.1 Energy Consumption and Growth Productivity

The application of LED technology to horticultural production represents an opportunity to use lighting energy efficiently to increase production of healthy, locally grown food. This aligns with the mission of the DOE SSL Program, which is to reduce lighting energy consumption. Analysis by the DOE SSL Program shows that lighting for horticulture consumes a significant amount of energy, particularly for indoor plant growth where electric lights provide all the necessary light. In greenhouses on the other hand, the electric lights provide lower light levels, are usually on less often, and are used seasonally to augment ambient sunlight. This means greenhouses consume less lighting energy per unit area. However, greenhouses account for the largest area of controlled environment agriculture.

Total energy consumed by horticultural lighting can be reduced by around 33% using LED lighting compared to previous lighting technologies. Improvements to light fixture efficiency can have significant impacts on total energy consumption in indoor growth settings. This impact is reduced in greenhouses, but it is still significant. LED fixtures are highly efficient with prospects for improved efficiency, although future efficiency improvements will be more modest as LED performance plateaus.

LED lighting technology also brings additional energy and productivity benefits. The lighting spectrum can be engineered for optimized plant responses and photosynthetic efficiency. LED lights can be instantly dimmed and turned on and off, so they can respond to changes in natural light levels in a greenhouse setting more quickly than conventional technologies like high-pressure sodium (HPS) lamps. This could also make them useful for grid-scale demand response. In addition, LEDs can pulse on and off. This may increase photosynthetic efficiency. None of these features are available with conventional lighting technologies. The higher efficiency of LED lighting means that light generation can be decoupled from heat generation in the light fixtures. This allows improved control of heating, cooling, and humidity in the indoor environment.

There was considerable discussion of lighting energy and productivity considerations with respect to growth setting – indoor versus greenhouse. Supplemental lighting needs in greenhouses are seasonal and require much less electric light than indoor systems to meet desired lighting targets. However, light levels and temperature conditions are a function of weather and seasonality, meaning they will need to be controlled accordingly. LED technology allows for consistent light levels through improved responsiveness. Sunlight transmitted into greenhouses comes with an associated solar heating effect that often requires cooling. However, it may be possible to engineer the glass or transparent exterior to reject more heat while allowing the light into the greenhouse. Electric lights also add to the heat load in a growth environment, but LEDs add less heat than conventional lighting technologies.

Full consideration of energy and required levels of environmental control for a given crop type are necessary for evaluating the economics of growing in controlled environments. The fundamental processes for converting light to biomass can be evaluated to understand the cost of light as a portion of the total crop production cost and pricing. New crop values enabled by LED technology also need to be considered, such as enhanced nutritional value, freshness (from local production), year-round production, crop color, newly enabled crops, and associated benefits of indoor production such as reduced water use and reduced use of pesticides or other chemicals. The productivity benefits beyond basic biomass yield and the energy benefits beyond light source efficiency make it difficult to apply a simple energy or productivity benefit model for controlled environment agriculture with LED lighting technology.

2.2 Lighting Product Performance and Characterization

There are existing performance testing and safety standards for horticultural lighting products. Performance standards can be applied to the measured lighting performance. Horticultural lighting efficacy is expressed in terms of photosynthetic photon efficacy (PPE). The unit for PPE is micro-moles of photosynthetic (400-700 nm) photons per second-watt which simplifies and abbreviates to µmol/J. Standard lighting performance test methodology LM-79 can be used with horticultural lighting with standard definitions for photosynthetic active radiation and conversion of measured results to horticultural metrics. Color qualities of light are critical for plant growth. Spectral power distribution (SPD) is measured as part of the LM-79 testing. Manufacturers typically provide an SPD or spectral quantum distribution (SQD). Participants at this meeting have advocated for standardized horticultural lighting performance labeling, similar to the Federal Trade Commission (FTC) Lighting Facts label. These labels could be generated from the standardized testing procedures. Labels would allow for easy comparison of all of the relevant attributes of competitive products. Variants of this label have been used, but have not yet been generally adopted by or required of the horticultural lighting industry. As a measure of output per energy, product PPE can be used as the key performance threshold for energy savings incentives.

LM-79 testing of horticultural lighting fixtures also measures far field optical distribution from the fixture so that lights can be arranged to achieve uniform light levels across the growth canopy. This is relevant and necessary for modeling lighting to achieve uniform light levels at a far-field distance from the target. For lighting placed very close to the target (less than 1 m), such as in a vertical farm configuration, near field optical measurement and modeling is necessary for achieving a uniform light level. A new measurement standard for measuring near-field optical distribution from horticultural lighting deployed near the plant canopy is nearly complete.

2.3 Yield and Plant Physiological Responses to Light

The relationship of yield and plant physiological responses to light quantity, quality, and duration is still an emerging area of research. Light is the key cardinal parameter for plant growth, but it is not the only parameter. When lighting technology is changed there are typically other environmental changes that can influence plant yield and physiological responses. Plant responses to light are different for different crops, cultivars of crops, and phases of the plant life. Additionally, yield of nutrients or other plant quality factors may be equally or more important than total biomass yield. So, there is no one optimal spectrum or light recipe for all plants. There is an opportunity to fine tune the spectrum for plants, particularly in terms of red, blue, and far-red content. Counting total photosynthetic photon emission from light sources is the current standard. However, biological efficiency weighting with respect to SPD could improve characterization and predictive performance of the lighting product.

Plant responses to intensity and photoperiod are also important to consider and may be impacted by LED technology. As mentioned earlier, LED lighting can be pulsed at a broad range of frequencies and duty cycles. This may increase photosynthetic efficiency. Lower intensity lighting applied over a longer period may influence photosynthetic efficiency as well. The idea is that the total daily light integral (DLI) of photons (and lighting energy required) would be the same but the yield would improve. This has the added benefit of requiring less total lighting wattage. Different crops may require defined photoperiods to enable plant development.

All of the key themes discussed support development of best practices for specific crop production in a specific growth setting. There is a huge diversity of crops, growth geographies, growth environment architectures, and genetic variants that need individual optimization. Horticulturists could also introduce new crops and new genetics that are optimized for the various controlled environment settings. Ideally, horticulturists will be able to predict and apply the optimal growth environmental and lighting conditions for any crop. This would enable production of the right crop in the best environment with consistent production and optimal economic prospects.

Appendix A: Participant Presentations

Provided descriptions are paraphrased summaries of the presented materials.

Kyung Lee, Guidehouse

This presentation covered the 2020 updated analysis of the energy savings potential of LEDs in horticultural lighting. The total lighted controlled environment horticultural area is estimated to be ~89 million ft^2. About 2/3 of this area is greenhouse space and 1/3 is indoor high intensity sole source lighting space. Only about 1% of the lighted growing area is used for vertical farming. Horticultural lighting site energy consumption is estimated to be 9.6 TWh. About 87% of this energy use is attributed to high intensity sole source lighting, with most of the remainder coming from greenhouse lighting. Vertical farming accounts for about 1% of this energy consumption. Switching all horticultural lighting to LED technology could save about 1/3 of the total energy consumption. This is equivalent to about $350M in electricity cost savings.

More information can be found here.

Kale Harbick, USDA ARS

Light uniformity from electric light fixtures in the greenhouse can be improved by arranging fixtures at different heights from the ceiling or by dimming certain fixtures. The uniformity results can be modeled using far-field modeling. This would apply for light fixtures at typical greenhouse ceiling heights or indoor settings where fixtures are at least several feet from the canopy. When light fixtures are placed closer to the canopy, as in vertical farms and some sole source indoor farms, near field modeling based on near field measurements should be used. The use of far field modeling will result in erroneous modeling of the intensity distribution.

Bruce Bugbee, Utah State University

In a greenhouse, sunlight provides light and heat. The ratio of provided photosynthetic photons to heat is 2 µmoles of light per 1 joule (J) of heat. This heat is managed by active cooling which can have a coefficient of performance of 5. Thus, 0.2 J of cooling energy are required per joule of heat. This results in a performance of 10 µmoles of light per 1 J of cooling. For the indoor growth setting, if a fixture with an efficacy of 3 µmol/J is used, then 1 J of energy is required to power the fixture and 0.2 J to cool the heat from the fixture. This results in 3 µmol/1.2 J which is 2.5 µmol/J. When heating at night is included, the greenhouse will require another 0.5 J of cooling. The indoor setting is assumed to be well insulated and require minimal cooling. With this cooling included, the performance of the greenhouse is now estimated at ~3 µmol/J and indoor is at ~2.4 µmol/J. Greenhouse glass with infrared (IR) reflective coating could improve the energy efficacy of sunlight by reflecting IR to achieve 4 $\mu mol/J_{thermal}$. This would increase the total efficacy of the greenhouse use of natural light to 5.7 µmol/J. This analysis shows the energy impacts of improved glass coatings on greenhouses.

Marc van Iersel, University of Georgia

Vertical farms consume the second most energy per floor area of any building type after data centers. Using longer photoperiods with lower photosynthetic photon flux density (PPFD) while maintaining the same daily light integral (DLI) can improve photosynthetic yield. Plants are resilient to modest short and long term fluctuations in PPFD. This can be used to develop lighting algorithms that co-optimize plant needs, variable electricity prices, and variations in sunlight-provided PPFD. Algorithms have been demonstrated for co-optimizing these factors.

David Bubenheim, Advisor to the University of California

The Global Controlled Environment Agriculture Consortium (GCEAC) is a global joint effort between California and the Netherlands to promote connected agriculture, food, and health solutions. Its mission is to support the next generation of the CEA industry with a global network of companies and universities. GCEAC plans to develop a network of field labs spanning across California and the Netherlands, create access to public and private R&D funding, and promote policies that support innovation and industry growth. The organization is developing a roadmap that will identify industry drivers, challenges, and potential solutions. Topics that will be covered include automation, data management, crop management, energy management, sustainability, workforce, and markets.

Erik Runkle, Michigan State University

There is no single optimum light spectrum for plant growth. The best spectrum will vary based on different growth situations and by the plant qualities desired by the cultivator. Often it is desirable to induce early flowering in plants to reduce production time. This can be achieved using far red in the spectrum. Adding blue light to the spectrum can promote compact plant growth, which is also desirable. However, these responses may vary for different species. In leafy greens, increased blue light resulted in decreased shoot mass, but it can bring out color or other desirable qualities. A balance must be found. Far-red light interacts with other wavelength ranges, especially blue light. The timing of different light spectra with respect to plant growth phase is an additional consideration. Light interacts with other environmental conditions. There may be trade-offs between biomass yield and quality attributes or other plant properties, such as desirably colored leaves.

Tessa Pocock, Soli Organic

The physical environment for indoor sole source lighting plant growth is controlled and optimized for consistent plant growth. At the same intensity, using phosphor-converted LED lighting versus cool white fluorescent lighting affects lettuce color. Higher intensity phosphor-converted LEDs can result in similar color yields. The lack of amber wavelengths in phosphor-converted LEDs relates to reduced anthocyanin yield. LED technology is less efficient at producing these desired wavelengths. Light efficacy of anthocyanin yield is different than yield efficacy. Plant biomass yield is also highly related to the uniformity of light intensity across the canopy. This is a critical factor for commercial scale growth.

Roger Buelow, AeroFarms

The cost of energy as a portion of the total cost of leafy greens is significant, so lighting efficiency and utility costs are important considerations. In terms of lighting effectiveness, fine tuning of the blue:red:far red ratio can improve plant growth. Practices for indoor growth of leafy greens need to be transferred to tomato growth in vertical farms. Vertical farm food safety SOPs can be standardized for the entire industry. New cooling methodologies, including cooling towers, phase change materials, water cooling, and waste heat capture would be valuable. Vertical farm lighting installations could also be used for grid scale power factor correction and grid demand response schemes. Machine vision could be an important production tool. Pulsing lights could enable increased photosynthetic efficiency.

Erico Mattos, GLASE Consortium

Lighting is a major cost within CEA. LEDs are ideal because they are dimmable. They can also work with grid demand response and variable pricing, as long as impacts on crop yield are understood. LED technology also allows for dynamic spectral control. However, this tool is seldom used in production because the optimal spectrum for different times is not understood. In addition, it is not clear that there is a cost benefit for this level of control. New CEA technologies must have improved mechanisms. More collaboration between funding agencies, researchers, and growers is needed. This could aid in developing technology integration and grow study performance with minimal commercial disruption. It is also important to communicate baseline performance expectations and perform research starting with meaningful production baselines.

Kyle Booth, Energy Solutions

Energy Solutions is focused on making farming more energy efficient and environmentally friendly by campaigning for minimum photosynthetic photon efficacy requirements and supporting programs that implement these performance thresholds. Energy Solutions has worked with California on Title 24 requirements for horticultural lighting efficacy. These standards may expand nationally through ASHRAE 90.1 requirements.

Jeff Lockner, UL

There are existing definitional and characterization standards and recommended practices for horticultural lighting, mainly ANSI/ASABE S640 and S642 and ANSI/IES LM-79 and RP-45. There are also standards under development for nearfield radiometric measurements and for reporting formats for test data. Third party accredited test labs provide objective, independent, calibrated measurements of horticultural product performance. UL8800 is a safety standard specific to horticultural lighting equipment.

A.J. Both, Rutgers University

In 2017, a product performance label was proposed to provide horticultural lighting buyers with clear and consistent product performance information. The label includes electrical, spectral, optical distribution, and efficacy information. Lighting is a 3-dimensional input to plants, but most PAR meters detect light on a surface. Spherical PAR meters could be deployed within a canopy to get a better idea of the 3D light field. There are numerous research challenges for horticultural lighting. These include reducing price, reducing energy consumption, optimizing light recipes, improving spectral and intensity uniformity, and validating real-world longevity of LED fixtures. On a broader scale, research is hampered by limited economic data from commercial greenhouses and human health and safety concerns with working in high-intensity light environments.

Stuart Berjansky, DesignLights Consortium

DLC is a nonprofit that works with industry partners and experts to develop technical requirements based on standards (such as UL standards). DLC maintains a list of qualified horticultural lighting products that meet defined technical requirements. Version 3.0 of the technical requirements is in development for 2022. Looking forward, DLC is developing standards for light pollution, controls integration, and improved metrics for predictably describing plant responses to light.

Derek Smith, Resource Innovation Institute

The mission of RII is to measure, verify, and celebrate the world's most efficient agricultural ideas. RII also provides education and best practices for CEA operators. RII is developing a benchmarking platform to quantify energy, water, and waste inputs and outputs for different CEA settings and crops. RII hopes to transition the CEA market to using best energy practices for a range of production environments.

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