U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Solid-State Lighting Program and USDA ARS:

Horticultural Lighting R&D Meeting

December 2022

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Disclaimer

DOE Solid-State Lighting Program and USDA Agricultural Research Service, "Horticultural Lighting R&D Meeting," December 2022.

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Solid-State Lighting Program
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Comments

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R&D Meeting Presenters

Stuart Berjansky	DesignLights Consortium
Roger Buelow	Aerofarms
Bruce Bugbee	Utah State University
Sofia Carvalho	Plenty
Kale Harbick	USDA Agricultural Research Service
Paul Kusuma	Wageningen University
Kai-Shu Ling	USDA Agricultural Research Service
Erico Mattos	Candidus
Neil Mattson	Cornell University
Marc van Iersel	University of Georgia
Melanie Yelton	Plenty

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1 Introduction

On December 14, 2022, experts in the field of horticultural lighting from industry, national laboratories, and universities gathered at the invitation of the U.S. Department of Energy (DOE) Solid State Lighting (SSL) Program and the U.S. 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 (R&D) opportunities for light-emitting diodes (LEDs) and horticultural usage of light

2. Bridge R&D efforts among horticultural researchers and LED technologists

3. Facilitate collaboration

4. Provide guidance to R&D agencies

The US DOE SSL Program and USDA ARS have an aligned interest in this topic because LED lighting technology provides the opportunity to not only reduce horticultural lighting energy consumption but also improve productivity. LED lighting technology provides new levels of efficiency and control in the delivery of lights to plants. LED lighting can be engineered to provide tailored spectral power distribution, tailored optical distribution, and precise intensity control while also providing higher photosynthetic photon efficacy compared to previous lighting technologies. These new levels of control require new understanding of horticultural physiological responses to light and their relationship to crop yield. The LED technology platform also requires new practical understanding for cost-effective deployment, particularly with respect to the new features offered by the technology.

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

2 Key Themes

The meeting format asked each participant to present findings and research directions from their own activities. In the discussions following the presentations, several recurring themes arose that could advance understanding:

- Fundamental and practical understanding of plant growth productivity – the conversion of photosynthetic radiation (light) and CO_2 into usable plant mass.

- Practical implementation of new lighting technology.

- Measurement and verification of energy, materials usage, and yield.

The discussion of spectral effects and characterization of lighting properties were less prevalent in this year's discussion. Characterization of light for plant growth applications is, for the most part, agreed upon, using the quantities of photosynthetic active radiation (PAR) from 400 to 700 nm. However, there is still the question of extending the upper bound of the PAR range from 700 nm to 750 nm, to include near infrared (IR) light that has been shown to be photosynthetically active synergistically with photons of other photosynthetic wavelengths. Using PAR quantification, photons within the photosynthetic wavelength range are defined to be equally photosynthetic. But, much like human based metrics for lighting characterization, which include total effective intensity, lumens for humans, and color quality metrics (CCT and CRI) for humans, color quality must be considered for plant growth in addition to total intensity (PAR) to achieve desired plant quality and optimize yield.

2.1 Plant Growth Productivity

LED lighting technology has greatly increased the photosynthetic photon efficacy (micromoles of photosynthetic photons per joule) of horticultural lighting compared to previous lighting technologies. LED technology has also enabled new levels of control of the spectral distribution of photons. It has enabled improved optical control and resulting delivery of photons to the plant canopy. However, the generation and distribution of photons only describes a portion of the full process of converting energy to usable plant biomass. The other portion of the process is absorption of photons by the plants and the conversion of photons with available CO_2 to usable biomass. The efficiency of this conversion process is a function of PAR intensity and spectrum as well as CO_2 availability, balanced with other critical growth inputs: temperature, air flow, humidity, nutrients, and water. Improving the efficiency of PAR absorption, improving biomass production processes, and increasing harvest index are additional means of improving the productivity of plant growth under electric lighting.

Fully controlled indoor environments further enable optimization of plant growth productivity. While greenhouses are controlled growth environments, they still experience changes in light level and temperature because of daily and seasonal fluctuations. In indoor facilities without sunlight, light is provided entirely by electric sources and is precisely controlled. Temperature and humidity can also be precisely controlled since these facilities have better insulation and protection from outdoor conditions. Fully indoor growth settings have demonstrated productivity levels for leafy greens, in terms of grams of fresh biomass per area per day, of 500 $g/m^2/day$, which approaches the theoretical limit.

The LED light platform enables efficient and precise delivery of photons. This capability can be combined with precision control of plant growth parameters to enable increased productivity per photon of light generated. Photons can be generated with much higher efficiency and more biomass can be grown per photon, which can result in a compound improvement in the productivity of plant growth. This can be quantified as yield per kilowatt hour of electricity input.

2.2 Practical Implementation of Horticultural Lighting Technology

The new capabilities of LED lighting technology enable new features and usage considerations that could further enhance the technology's value. LED lighting technology is fundamentally dimmable and can be turned on and off instantaneously. These control capabilities enable integrated systems that can respond to fluctuating daily sunlight levels in greenhouses, as well as variable electricity pricing for greenhouses and indoor growth facilities. Controls algorithms can be developed to take advantage of variable electricity pricing and run lights when electricity prices are low. Many plants can tolerate fluctuations in light levels as long as the target daily light integral (DLI) is achieved.

As with general illumination, it is beneficial to have interoperability among light fixtures and controls from different manufacturers. In horticultural production, lights are often dimmed or turned on/off by a greenhouse management system, and various interfaces need to be deployed to ensure communication between systems. Many horticultural fixtures use 0-10V wired dimming, so it should be possible to use a common dimming signal to control lights from different manufacturers. Wireless dimming systems, which remove the need for installing controls wiring and make it easier to modify lighting zones, are beginning to reach the market.

Greenhouses can also benefit from reconsideration of the transparent envelope and the greenhouse architecture and orientation. In a greenhouse, sunlight comes with thermal radiation that requires active cooling, usually achieved with evaporative pads and ventilation. Indoor farms use electric light that requires electricity and active cooling, usually mechanical cooling which is much more energy intensive than evaporative cooling. Glass that is engineered to transmit photosynthetic light and reject infrared, thermal radiation could greatly reduce the energy required for cooling. Advanced modeling software can provide improved calculations of greenhouse light transmittance to the plant canopy for different greenhouse orientations, roof pitches, and glazing materials with respect to varying sky brightness, time of year, and geographic location. This will result in more precise greenhouse designs based on the specific site and historical and anticipated weather conditions. These improvements can result in nominal increases of incident light, which add up to meaningful increases in total yield.

2.3 Measurement and Verification

Technology and productivity advancements resulting in increased yield per unit input energy, water, and nutrients need to be measured and validated. This is challenging due to the diversity of controlled environment agriculture (CEA) production facilities with different levels and resolution of input measurement. In indoor CEA settings, lighting photoperiod, intensity, and energy consumption are highly predictable. For greenhouses, variations in lighting may occur due to weather conditions and seasonal daylight. These variations can result in differences in yield and/or crop morphology. It is important to be able to track lighting usage in greenhouses to monitor energy consumption and understand relationships between weather, ambient sunlight levels, electric light usage, and, ultimately, yield. This information is crucial over the course of a crop cycle, the entire year, and the life of the greenhouse. It will facilitate understanding and resolving energy costs and yield and enable system improvements. Lighting monitoring needs to be applied with water, nutrient, temperature, ventilation, and CO_2 supplementation monitoring so that all relationships can be analyzed. This will lead to productivity and efficiency benefits.

Appendix A: Participant Presentations

The presentations are listed in the order the speaker presented.

Marc van Iersel, University of Georgia, "Optimizing Electricity Usage in Controlled Environment Agriculture"

Marc van Iersel, Professor at the University of Georgia's College of Agriculture and Environmental Sciences, discussed optimizing electricity use and lighting for indoor agriculture. He began by noting that plants can tolerate both short and long-term fluctuations in light level, and that this allows for use of electricity saving controls in indoor agriculture. He proposed that supplemental lighting for crops should account for the crops' ability to use the light efficiently, variable weather conditions, and the real-time price of electricity. He then walked participants through his group's approach for optimizing lighting controls schemes based on these parameters. van Iersel said that although their approach worked well (reducing electricity use by about 35% and maintaining crop performance), challenges such as obtaining real-time electricity price data remain. At the meeting, van Iersel said that his group would continue to work on refining their approach. The group hopes to use it to reduce costs for indoor farms, help utilities optimize their grid strategies, and lower produce prices for consumers.

Sadly, Marc van Iersel passed away on April 20, 2023. He is remembered within the horticulture and CEA research community as an innovative researcher and educator whose work advanced basic horticultural scientific understanding and paved the way for growers to embrace the benefits of LED technology.

Bruce Bugbee, Utah State University, "Greenhouse vs. Electric Agriculture: Light to Heat Ratio"

Bruce Bugbee, Professor at Utah State University's College of Agriculture and Applied Sciences, compared the light to heat ratios of greenhouse and electric agriculture. His presentation mostly consisted of a step by step approach for calculating the ratios for both methods in terms of micromoles (µmol) of light per joule (J) of heat. Bugbee started out by showing that the light to heat ratio for sunlight is 2 µmol/J. Based on this, he calculated the light to heat ratio for greenhouses. He assumed that the coefficient of performance (COP) for the greenhouse's cooling system was 5, so the energy required to cool the greenhouse for every joule of heat from the sun was 0.2 J. He also included the energy needed to heat the greenhouse overnight, which he assumed was 0.5 J. He arrived at a light to heat ratio of 3 µmol/J for greenhouses. The calculation for electric agriculture was similar, in that the same COP was used for cooling. However, the light to heat ratio for electric light was assumed at 3 µmol/J. The night heating requirement was assumed at 0.05 J. The calculated electric agriculture ratio was 2.4 µmol/J. Thus, Bugbee believes that greenhouse farming will be more energy efficient than electric agriculture in the long run. He also went on to show that when reflective IR coating is used in a greenhouse, the light to heat ratio can improve to 5.7 µmol/J.

Kale Harbick, USDA Agricultural Research Service, "Natural Light Modeling in Greenhouses"

Kale Harbick, Research Agricultural Engineer at USDA Agricultural Research Service, presented on natural light modeling in greenhouses. The primary focus was the relationship between building orientation and geometry and the Daily Light Integral (DLI), which is the number of photosynthetically active photons that are delivered to a specific area over a 24-hour period. Harbick's method to elucidate this relationship first involved dividing the sky into "patches" that were approximately the same size each. He then projected the sun's light onto the model building's surfaces using a modeling software. Finally, he calculated the transmittance and projected the light onto the plant canopy. He found that there were similar results for a range of latitudes in the contiguous United States. He also found that a lower roof pitch, a north/south orientation, a lower gutter height, and a square footprint were all more favorable for maximizing DLI inside a greenhouse. In the future, Harbick plans to experiment with intermediate orientations and other parameters to determine their effect on DLI.

Paul Kusuma, Wageningen University, "How Much Can We Expect from Spectrum?"

Paul Kusuma, Postdoctoral Researcher at Wageningen University, explained how spectrum plays a role in electrically lit agriculture and the extent of its effect. He started out by noting that spectrum can increase or decrease plant yield by up to 50%, although 5-20% changes are more typical. However, questions remain regarding the quality of produce grown using these methods. Kusuma then discussed the relationship between indoor agriculture profitability and energy consumption. He said that during the first Autonomous Greenhouse challenge, a team using artificial intelligence (AI) to optimize timing of lighting and amount of electricity use had a 17% higher profit margin than reference growers. In the second challenge, the team using AI was twice as profitable as reference growers.

Stuart Berjansky, DesignLights Consortium, "2022 USDA and DOE Horticulture Lighting Discussion Meeting"

Stuart Berjansky, Technical Director at DesignLights Consortium (DLC), provided an update on DLC's focus areas and fields of interest before making some suggestions for further research and development. DLC is a large industry organization "whose mission is to achieve energy optimization by enabling controllability with a focus on quality, people, and the environment." Berjansky shared that DLC, an organization mostly made up of utilities, is concerned about the "duck curve" with renewable energy and hopes that indoor agriculture can be an effective demand response tool. He outlined changes coming in DLC's recently released horticultural lighting standard. The new publication represents version 3 of the standard. For R&D, he said that DLC would like to see better objective data on energy use for facilities that rely solely on electric lighting for agriculture and the impact of demand response measures on their productivity. He also called for more research on horticultural lighting energy efficiency and facility light pollution.

Sofia Carvalho, Plenty, "Plenty Company and Technology Overview"

Sofia Carvalho, Senior Lighting Scientist at Plenty, presented on Plenty's approach to vertical farming and research. She described how Plenty independently developed almost all of the technology they use in their systems, including the lighting. Plenty's lighting allows the company to change the plants' spacing and the spectrum the plants are exposed to as the plant matures. Carvalho also noted that the company is continuing to investigate this field, with multiple teams working on improving plant yield and profit using lighting. She concluded by describing Plenty's new facility in Compton, California and stating that yield targets for leafy greens are between 500 and 900 g/m^2/day.

Roger Buelow, Aerofarms, "Aerofarms Leads the Way"

Roger Buelow, Chief Technology Officer at Aerofarms, gave an overview of the company's history, progress, and directions for future research. Aerofarms is a vertical farming company. Buelow began by talking about the company's founding in 2004 and noted that Aerofarms has proprietary technology for most of its systems. The company is constantly updating and improving these systems. Buelow believes that as lighting technology and relevant controls progress, lighting will make up less of the potential savings for vertical farming companies. He thinks that HVAC and humidity control will be the next important focus area for industry improvement and expects that the transition will happen in the next 3-5 years. Buelow also argued that it is important to consider how other countries view vertical farming and how they will implement the technology to solve their own problems.

Erico Mattos, Candidus, "DOE Meeting"

Erico Mattos, Co-Founder of Candidus, spoke on the advantages of dynamic lighting control in facilities that use electric lighting. One major advantage is dimming. Dimming allows for on-demand control of the lighting conditions affecting crops. It can provide consistency and the ability to match different crops' lighting requirements. Another benefit provided by dynamic lighting control is the ability to alter the daily light integral. This allows for consistent crop production year-round. This ties into the third advantage, the ability to shift electricity use to times when prices are low. This can significantly impact a facility's profit margin. Finally, Mattos mentioned spectrum control as an advantage, but said that it was currently cost prohibitive.

Mattos concluded by calling for accurate sensing and technology integration, including open communications platforms that can interface with other building controls.

Kai-Shu Ling, USDA Agricultural Research Service, "Controlled Environment for Indoor Fruit and Vegetable Production"

Kai-Shu Ling, Research Plant Pathologist at USDA Agricultural Research Service, gave an overview of current USDA ARS projects. He began by describing the team's progress on indoor tomato production. There are five objectives for the project, one of which is energy efficiency and research on LED lighting sources. USDA locations around the country are participating. Next, Ling discussed USDA ARS's shipping container based vertical farming project in Charleston, South Carolina. The project will have 16 CEA shipping containers installed at that location. The containers are equipped with hydroponics systems and insulation. Newer containers will have custom LED light spectrum modulation and solar panels installed on the outside of the containers. Production of leafy greens, strawberries, and sweet potatoes have been successful in the containers, but improvement is needed for fruiting vegetables such as tomatoes and edamame.

Neil Mattson, Cornell University, "Cornell University Research and Future Prospects for Horticultural Lighting"

Neil Mattson, Professor and Greenhouse Extension Specialist at Cornell University, discussed his research group's progress and future research plans for horticultural lighting. Mattson began by describing what he views as the barriers to LED adoption. He mentioned their high capital cost, the difficulty of incorporating complex control capabilities into existing climate control systems, a lack of LED familiarity among growers, and a rapidly changing technology landscape as obstacles. He then moved on to explain the Greenhouse Lighting and Systems Engineering (GLASE) project, which aims to reduce lighting electricity use in greenhouses by 70% relative to 2014 levels. One experiment run by Mattson's group showed that averaged across the year, plants exposed to high pressure sodium (HPS) lighting had no difference in yield relative to those exposed to LED lighting. Mattson finished by highlighting the importance of far-red radiation for plants in sole-source lighting. He presented some images showing that plants exposed to more far-red radiation grew faster than other plants. Mattson concluded by describing future research priorities, including controlled environment agriculture electricity concerns and the interaction of light spectrum with canopy temperature, nutrition, and water use efficiency.

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