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Wavelength-Selective Solar Photovoltaic Systems: Powering Greenhouses for Plant Growth at the Food-Energy-Water Nexus

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Key Points:

- Wavelength-Selective Photovoltaic Windows (WSPVs) absorb a portion of incoming solar radiation to help generate electricity, and also transmit a portion of the light to drive photosynthesis by plants below the windows
- Plants grown under WSPVs show few negative effects of the altered light quality and quantity on photosynthesis, fruit number, and fruit biomass
- WSPVs could allow for greater adoption of installed solar electricity generation capacity that is more sustainable in terms of materials, lower in cost, and more efficient than conventional silicon-based photovoltaic cells

Supporting Information:

- Supporting Information S1

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Abstract Global renewable electricity generation capacity has rapidly increased in the past decade. Increasing the sustainability of electricity generation and the market share of solar photovoltaics (PV) will require continued cost reductions or higher efficiencies. Wavelength-Selective Photovoltaic Systems (WSPVs) combine luminescent solar cell technology with conventional silicon-based PV, thereby increasing efficiency and lowering the cost of electricity generation. WSPVs absorb some of the blue and green wavelengths of the solar spectrum but transmit the remaining wavelengths that can be utilized by photosynthesis for plants growing below. WSPVs are ideal for integrating electricity generation with glasshouse production, but it is not clear how they may affect plant development and physiological processes. The effects of tomato photosynthesis under WSPVs showed a small decrease in water use, whereas there were minimal effects on the number and fresh weight of fruit for a number of commercial species. Although more research is required on the impacts of WSPVs, they are a promising technology for greater integration of distributed electricity generation with food production operations, for reducing water loss in crops grown in controlled environments, as building-integrated solar facilities, or as alternatives to high-impact PV for energy generation over agricultural or natural ecosystems.

Plain Language Summary Increasing the sustainability of food production will require development of new mixed-use technologies. Here, we describe novel electricity-generating windows (Wavelength-Selective Photovoltaic Systems, WSPVs) suitable for use in greenhouses for growing plants. The windows use an embedded dye to transmit some energy from sunlight to thin solar panels along the windows. The dye changes the nature of light passing to plants below, but we show few substantial changes to photosynthesis or fruit number or fresh weight. There is a small water savings associated with photosynthesis. Results show minimal lasting effects of growth under WSPVs on plant physiology and development, thus WSPVs represent a new wedge for decarbonizing the food system.

1. Introduction

Human activities since the onset of the Industrial Revolution have resulted in increased concentrations of atmospheric carbon dioxide and other greenhouse gases (GHGs), and widespread conversion of the global terrestrial surface area to agriculture and urbanization (IPCC, 2013). Avoidance of dangerous levels of climate change in the near future requires mitigation of GHGs through transitional fuels-switching (i.e., from coal to natural gas) and a greater reliance on a broad, integrated portfolio of solar, wind, geothermal, biomass, and other alternative sources for electricity generation.

Global solar energy production has increased dramatically in recent decades, yet there is tremendous opportunity for further expansion. Installed renewable electricity generation capacity grew globally from 750 to over 1200 GW between 2000 and 2011 (Energy Efficiency & Renewable Energy (EERE), 2013). Of total global electricity generation, renewables account for 22% or 4309 TWh, of which wind and solar energy (photovoltaic [PV] and solar-concentrating combined) are the fastest-growing renewable energy sectors. China, Germany, Japan, the United States, and Italy are the top five countries for installed solar PV electricity generation, where growth in electricity generation from solar PV increased more than 50-fold between 2000 and 2011 (U.S. EIA, 2016). Despite the increases in global installed solar electricity generation capacity

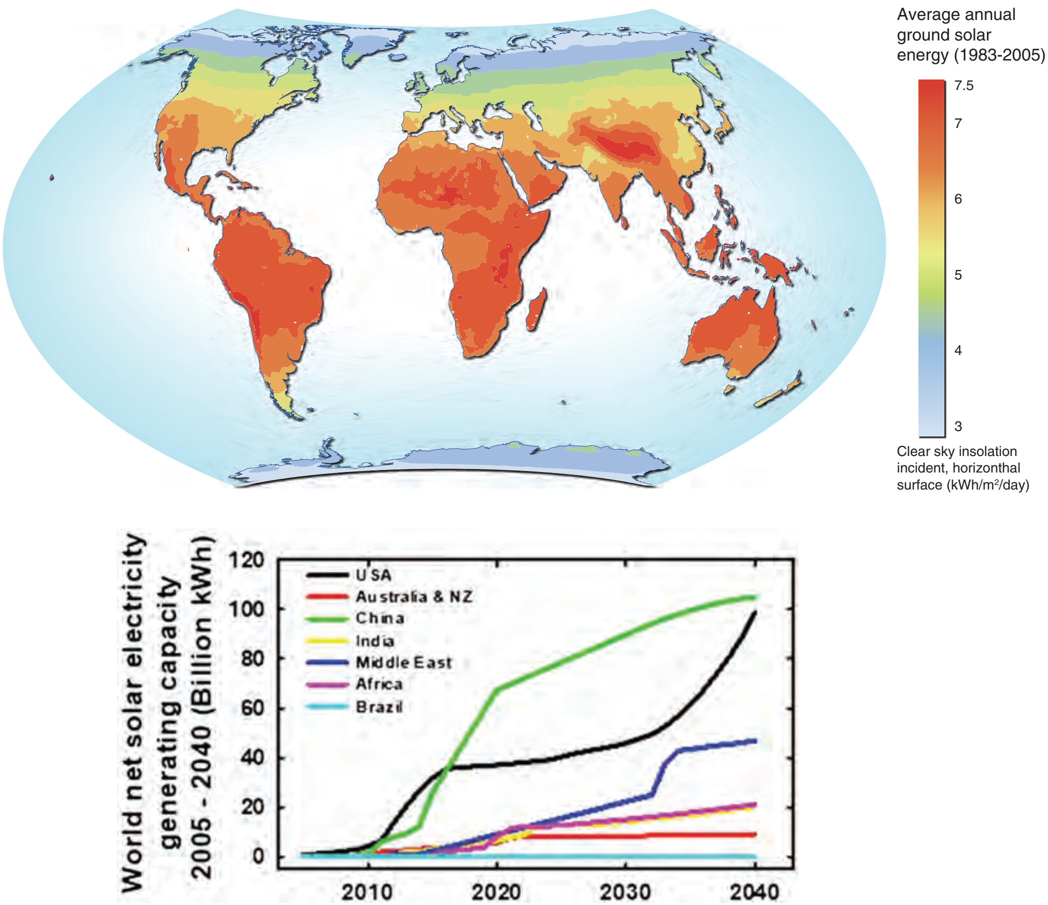

Figure 1. Average global distribution of surface solar radiation interception for the period 1983–2005 (top). Image source: UNEP/GRID-Arendal (http://www.grida.no/graphicslib/detail/natural-resource-solar-power-potential_b1d5), courtesy of Hugo Ahlenius. Bottom: Projected global electricity generation potential for the period 2005–2040. Source: U.S. Energy Information Agency (July 2013).

over the past decade, utility-scale solar facilities have generally not been installed in regions where surface shortwave solar radiation interception is highest (Figure 1, top). Worldwide net solar electricity generating capacity is projected to grow to close to 270 billion kWh by 2040 (Figure 1, bottom). Increasing the market share of solar electricity generating technologies will require innovative technological advances that reduce manufacturing and installation costs of solar panels, improvements in PV cell conversion efficiencies, and adoption in novel applications.

The need to transition electricity and other energy technologies to more sustainable pathways can sometimes conflict with other desirable policy or management goals, such as feeding a growing human population or preservation of biodiversity and ecosystem services. In the United States, California often leads the way in providing incentives for solar energy installation in homes and businesses, and the state is also a major agricultural producer. California enacted the Global Warming Solutions Act of 2006 (Assembly Bill 32) to address climate change by reducing GHGs throughout the state. One of its requirements is for 33% of electricity to come from renewable sources by 2020, meaning that California could need around 550 km^2 (100,000 acres) of land to meet its renewable energy targets from solar energy (Elkind, 2011). This would likely require conversion of agricultural, grazing, or desert lands to new uses, but such facility development could conflict with producing food or conserving native biodiversity. In 2012, 1553 km^2 (about 285,000 acres) of six southwestern U.S. states (Arizona, California, Colorado, Nevada, New Mexico, and Utah) were designated by the U.S. Bureau of Land Management, for development of utility-scale solar energy facilities, primarily on desert lands (Bureau of Land Management (BLM), 2012). The impacts of the land use conversion associated with this scale of solar development on land surface albedo, surface-atmosphere energy exchanges, and fluxes of carbon and water between soils, ecosystems and the atmosphere are

Figure 2. Glasshouse constructed with Wavelength Selective Photovoltaic (WSPV) panels, at the University of California Santa Cruz Arboretum. The WSPVs consist of polymethyl methacrylate (PMMA) plastic embedded with luminescent perylene red dye. The electricity generated by narrow photovoltaic strips (black lines in red panels) powers the operation of the glasshouse fans, microclimatic monitoring sensors, and data loggers. Photographs by Glenn Alers.

largely unknown. In this regard, a recent study demonstrated the Photovoltaic Heat Island Effect in Arizona, United States, in which air temperatures at night are 3–4 °C warmer over a solar PV installation than over adjacent wildlands (Barron-Gafford et al., 2016).

Many factors have led to a greater integration of solar PV on farmlands worldwide (Alnaser & Alnaser, 2011; Xue, 2017). Distributed electricity generation is a growth industry in 2017, and various factors have incentivized land-use conversion from crop growth to PV arrays integrated with utility-scale generation in some places (Ryan, 2016). Adoption of solar has occurred at various scales, from powering pumps on fields, to co-cropping or managing animals under solar panels (Baum et al., 2009). The mixed-use approach has been called "agrivoltaics," or "solar farming" (Dinesh & Pearce, 2016; Santra et al., 2017; Xue, 2017). Despite the growth of conventional silicon-based photovoltaics (Si-PV) on farmlands, many opportunities exist to develop new wedges to decarbonize the food system. Here, we describe a novel means for solar electricity generation within the glass or plastic windows of a greenhouse, Wavelength-Selective Photovoltaic Systems (WSPVs), which could enable solar electricity generation on a wide-scale in production, research, horticultural, backyard, and subsistence greenhouses worldwide.

1.1. Wavelength-Selective Photovoltaic Systems (WSPVs)

WSPVs (Figure 2) were developed based on the technology utilized in luminescent solar concentrators (LSCs) (Sholin et al., 2007). The transparent portion of the greenhouse roof serves to extend the solar collection area of the opaque PV cells, by absorbing some of the incoming solar radiation at certain wavelengths, and transmitting that energy laterally within the dyed plastic. The absorbed energy is transferred within the dyed plastic and delivered to the narrow PV cells that are integrated into LSCs. As a result, WSPVs achieve a gain of two or more in power per unit area by placing wavelength-selective luminescent absorbers between Si-PV panels (Corrado et al., 2013). The WSPV is effectively a building-integrated PV (BIPV) window. Whereas other BIPV window technologies have emerged, many are very costly and none are designed to accommodate the solar spectrum required for plant photosynthesis and growth in greenhouses (Jelle et al., 2012; Oliver & Jackson, 2001).

Key to the efficiency of the WSPVs are LSCs. An LSC utilizes a luminescent material to absorb solar radiation, which waveguides a fraction of the photons to optically attached Si-PV cells where they are converted into electricity (Currie et al., 2008; Debije & Verbunt, 2012; Goetzberger & Greube, 1977). LSCs have been limited in power efficiency by low absorption of the solar spectrum, self-absorption of the emitted light, and waveguide losses. The WSPV improves the power efficiency of LSCs by (1) using a luminescent material that efficiently absorbs and emits radiation without excessive re-sorption and quenching, (2) the use of face-mounted (rather than edge-mounted) PV cells, which yields substantial power gains through direct illumination of the PV cell, and (3) the much shorter distances that the absorbed light energy needs to travel before being converted to electrical power.

1.2. The Power Efficiency of WSPV Modules

The power efficiency of a WSPV module (η_{WSPV}) is determined by the power efficiency of the PV cells, luminescent material, and other components, corrected for the relative area of the transparent LSCs versus the opaque PV cells. The luminescent material contributes to the overall power efficiency based on the photoluminescence efficiency, the area of the luminescent collector, the fraction of the solar spectrum absorbed, the proportion of wavelengths transmitted to the PV cells, and conversion efficiencies. The overall power efficiency can be summarized as:

$$\eta_{WSPV} = \left(A_{PV}/A_{WSPV}\right)\eta_{PE} + \left(A_{LSC}/A_{WSPV}\right)\eta_{PL} \times \eta_{abs} \times \eta_{WG} \times \eta_{dc} \times \eta_{MPE}.$$

where A_{PV} is the area of the PV cell, A_{LSC} is the area of the LSC, A_{WSPV} is the area of the WSPV ($A_{WSPV} = A_{PV} + A_{LSC}$), η_{PE} is the power efficiency of the PV cell, η_{PL} is the photoluminescence efficiency, η_{abs} is the fraction of the solar spectrum absorbed, η_{WG} is the fraction of light that is successfully waveguided to the PV cell (this term includes self-absorption), η_{dc} is the efficiency of the energy conversion process from higher energy to lower energy photons, and η_{MPE} is the power efficiency of the PV at the wavelength of the emitted light (i.e., the monochromatic power efficiency).

Luminescent organic materials can have $\eta_{PL} > 85\%$, $\eta_{abs} > 42\%$, η_{dc} of >80%, and a η_{WG} of >70% (up to 10 cm travel distances). Combined with a 20% efficiency Si solar cell, with a monochromatic efficiency (η_{MPE}) of 30% at 700 nm, the luminescent portion alone would have a theoretical power efficiency of 6%. The overall theoretical WSPV power efficiency for 5× concentration (i.e., $A_{PV}/A_{WSLC} = 0.20$) would therefore be $0.20 \times 20\% + 0.80 \times 6\% = 8.8\%$ with over half of the power coming from the luminescent material. The Carter and Alers laboratory has fabricated initial prototypes of WSPV comprised of 30% SunPower PV and 70% LSC embedded into polymethyl methacrylate (PMMA). This material absorbs approximately 64% of the spectrum between 380 and 620 nm, or approximately 27% of the solar spectrum. The theoretical power efficiency would therefore be:

$$0.30 \times 20\% + 0.7 \times (0.85 \times 0.27 \times 0.8 \times 0.75 \times 0.35) = 6\% + 3.4\% = 9.4\%$$

where commercial solar PV panels have an efficiency in 2017 of 15–17%. Under these conditions, the LSC (luminescent dye in PMMA) provides a gain in power, P due to direct illumination of the PVs and the contribution from the LSCs:

$$\text{Gain} = \left[P^{PV} + P^{LSC}\right] / \left[P^{PV}\right] = 1.56.$$

1.3. Performance, Durability and Cost of WSPVs

Research in Carter's and Alers' laboratories led to the development of WSPVs, for which the monthly electricity-generation of a single panel of area 0.865 m^2 is shown in Figure 3. The total monthly electricity generated by a 3.05 by 7.3 m greenhouse if each panel was of the leading panel design (there were a variety of designs tested) would be 0.5 kWh. The WSPV panels are comprised of 12% Si PV and 88% LSC. This material absorbs approximately 40% of the PAR spectrum, or approximately 20% of the solar spectrum that is usable by Si. The material effectively increases the red part of the spectrum, as shown in the photoluminescence spectrum of Figure 3, by approximately 10%. The window with the most optimized geometry and cell type yielded a flash-tested power conversion efficiency of 5% (Corrado et al., 2013.) In the field, the actual efficiency was 4%, compared to a control window which had solar cells attached to clear glass with no red dye material, with an efficiency of 3%, exhibiting an enhancement effect >30% due to the LSC.

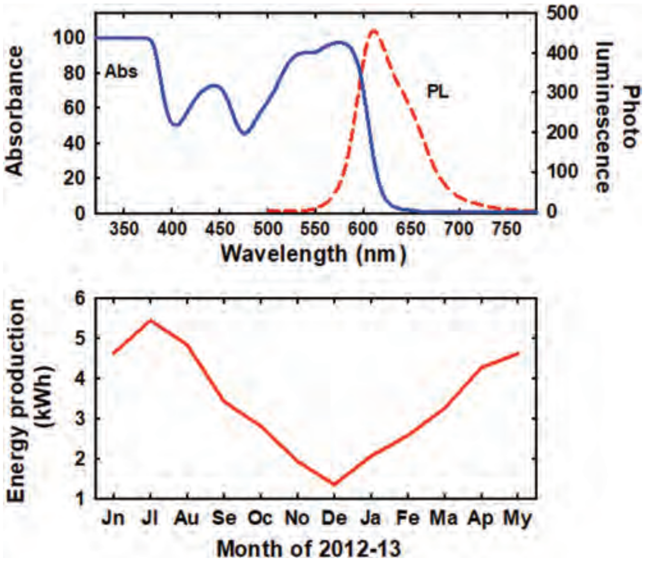

Figure 3. (Top) Dye absorption spectrum (Abs, solid line) and photoluminescence emission spectrum (PL, dashed line) for dye in polymethyl methacrylate (PMMA). (Bottom) Monthly energy production of a single panel in glasshouse with Wavelength Selective Photovoltaic (WSPV) roof.

Performance and production costs of WSPVs can be lower than standard Si-PV cells. The WSPV technology reduces PV module cost per Watt by up to 50% by replacing relatively expensive Si-PV (~$300 per m^2 at 20% efficiency) with a very low cost (~$10 per m^2) luminescent sheet. Material costs of the WSPV for a greenhouse are approximately $30/m^2 for the narrow PV cells + $10/m^2 for luminescent film + $5/m^2 for hardware = $45/m^2. At 7% power efficiency, the power price is about $0.65/W, an approximately 40% decrease compared to the Si-PV cell. The WSPVs generally have higher PV performance under partial shading and diffuse lighting conditions; concentrated light, lack of angle dependence, and ability to absorb solar photons from both sides increases performance under low and diffuse lighting conditions and enables efficiency gains via reflected light. The WSPV technology may also generate lowered costs through streamlining the development of new PV technologies. For example, the use of WSPVs (instead of Si-based modules) would enable a more rapid transition to market for new U.S. thin-film PV technologies, such as cadmium–telluride (CdTe), copper indium gallium selenide (CIGS), and gallium-arsenide (GaAs) solar cell materials.

The environmental costs of solar electricity generation may be reduced depending on how the technology is deployed, integration with emerging technologies, and how costs are quantified. Embedded system installation costs can be reduced somewhat because the land on which the PV is installed can be used simultaneously for food production. By comparison to Si-PV, WSPVs consume fewer toxic and rare materials, as over 80% of the active PV area consists of earth-abundant and nontoxic organic materials. An accounting of the full costs of WSPVs in comparison to Si-PV awaits a comprehensive life cycle analysis.

1.4. Do Plants Grow Normally under Electricity-Generating WSPV "Solar Windows"?

Plants detect the quantity, quality, direction, and duration of light in their surroundings using a variety of photoreceptor pigments (Fankhauser & Chory, 1997; Kami et al., 2010). Chlorophyll is the primary photoreceptor pigment that powers the photosynthetic fixation of CO_2 into carbohydrate products (Nobel, 2005; Taiz & Zeiger, 1991). A diverse array of other photoreceptors (e.g., cryptochromes, phototropins, phytochromes, and the Zeitlupes) sense UV-A, UV-B, blue, green, orange, red, and far-red wavelengths of the electromagnetic spectrum, and regulate photomorphogenetic processes such as germination, de-etiolation, stem elongation, leaf size and shape, stomatal opening, and the transition to flowering (Smith, 2000). Absorption of light by a photoreceptor molecule generally induces a signal transduction pathway that leads to gene expression and altered photomorphogenesis. The ensuing responses by the plants are complex and are often coordinated through the action of more than one photoreceptor type (Quail, 2002).

The utility of WSPVs for distributed generation in greenhouses can only be realized if plants can be grown that develop and function like those grown under conventional greenhouse window materials. The altered quantity and quality of light transmitted by the luminescent dye material embedded in PMMA (Figure 3) was specifically chosen to remove mostly green and some of the blue wavelengths of light, while enhancing the red fraction of the spectrum where photosynthetic activity is highest (Brown et al., 1995; Kim et al., 2004; McCree, 1972). Ideally, the light transmitted through the WSPVs could power photosynthesis, thereby

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enabling electricity generation for greenhouse support while simultaneously driving plant growth below. However, the population of transmitted photons is depleted in blue and green wavelengths, and the integrated amount of energy transmitted is 5–30% lower than companion clear greenhouses (depending on season, time of day, and cloud cover.) Thus, questions arise about the performance of plants grown in greenhouses with integrated WSPVs that have altered the transmitted quantity and quality of light.

Does the altered light quality and quantity affect photosynthesis for plants under the WSPVs? We have measured the responses to varying light levels (photosynthetically active radiation, PAR; 400–700 nm) for tomatoes (*Lycopersicon* cv. Early Girl) using the classical light response or *A*–*Q* model (Ögren & Evans, 1993). For low light intensities, photosynthetic CO_2 uptake into leaves was about the same for plants under clear or dyed WSPVs (Figure 4a). Above about one-quarter of full sunlight (500 μmol photons m^{-2} s^{-1}), *A* was light-saturated under both clear and dyed WSPVs, and was about 20% lower for plants under WSPVs. The patterns of CO_2 uptake were mirrored by the rate of electron transport through Photosystem II (PSII) within chloroplasts (ETR; Figure 4b); ETR supports regeneration of the carboxylation substrate for CO_2 fixation (Taiz & Zeiger, 1991). ETR increased similarly for plants under clear or dyed windows, but light-saturated ETR was about 12% lower than under clear windows at PAR = 500 μmol photons m^{-2} s^{-1}, and 30% lower than for plants under clear windows at PAR = 2000 μmol photons m^{-2} s^{-1}. Overall, light-saturated photosynthesis is marginally lower for tomatoes grown under WSPVs than under conventional windows. They may be quite useful for growing plants species that prefer a certain degree of shade, too.

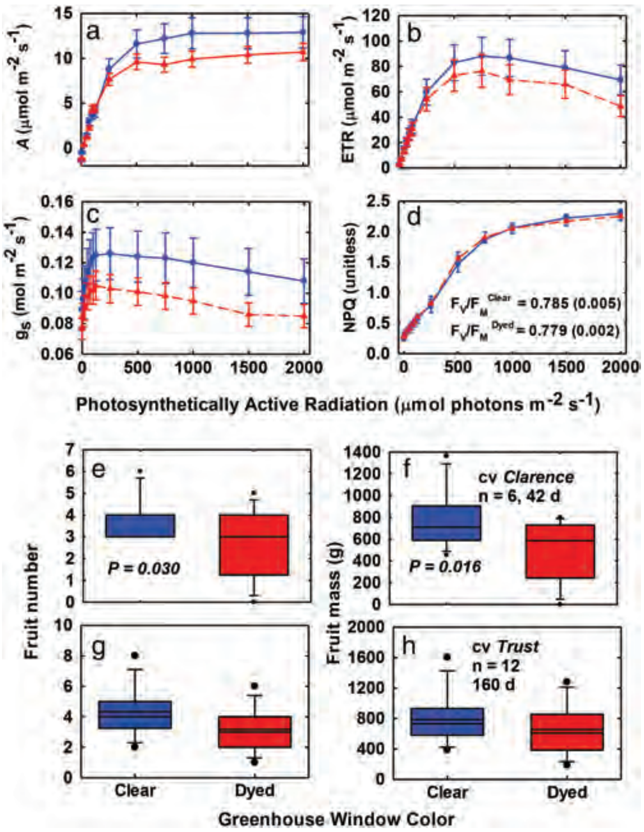

Figure 4. Photosynthesis and development of tomatoes grown under WSPVs and clear greenhouse windows. (A) Photosynthetic CO_2 assimilation (*A*, μmol CO_2 m^{-2} s^{-1}) as a function of photosynthetically active radiation (PAR; 400–700 nm). A PAR of 2000 μmol photons m^{-2} s^{-1} is roughly equivalent to full sun in the temperate zone at noon in early summer. (B) The rate of electron transport (ETR, μmol electrons m^{-2} s^{-1}) through PSII in chloroplasts, which links the light reactions with CO_2 fixation into sugars. (C) Stomatal conductance to water vapor (g_s, mol H_2O m^{-2} s^{-1}) in response to PAR, an indication of water use by leaves. (D) Nonphotochemical quenching (NPQ, unitless) in response to PAR, reflecting in part photoprotective energy dissipation. Blue solid lines are for plants under clear PMMA plastic and red dashed lines are for plants under luminescent-dyed PMMA plastic. Data are means ± SE ($n = 6$). Panels E–H: Total number fruit per plant (E, G) and mass of fruit per plant (F, H) for tomato (*Lycopersicon esculentum* cv Clarence (E, F) and cv Trust, (G, H)) grown under clear plastic or red luminescent dye in plastic (PMMA). Data are means (horizontal black line), standard error (wide colored bars), standard deviation (whiskers) and outliers (points) for the number of plants and time duration shown. Blue bars correspond to plants under clear PMMA and red bars are for plants under dye in PMMA.

Do plants use more or less water when grown under WSPVs? The loss of water from leaves can be estimated via the stomatal conductance to water vapor (g_s, Figure 4c). For plants under WSPVs, g_s was about 25% lower than for plants under clear windows when compared at a PAR of 1500 μmol m^{-2} s^{-1} (Figure 4c). This difference is greater than for the reduction in *A* or ETR for plants under dyed versus clear windows. We hypothesize that this discrepancy is due to the blue-light effect on stomata under the WSPVs (Inoue & Kinoshita, 2017), but this needs rigorous testing. Perhaps more importantly, the intrinsic water use efficiency (A/g_s) is about 126 μmol CO_2 (mol H_2O)$^{-1}$ under dyed windows, about 5% higher compared to clear windows. This suggests that there is a small water savings associated with growth of tomatoes under WSPVs.

Are plants under the WSPVs benefitting from slightly lower values of incident sunlight compared to plants under relatively brighter clear windows? When sunlight exceeds the saturation point for photosynthesis, various processes are induced to avoid damage due to over-excitation and damage within chloroplasts. To the extent that the WSPVs reduce light intensity, they somewhat act as if the PVs were wider, thereby shading plants and reducing the potential for high light induced damage. The upregulation of photoprotective processes can be collectively assessed by measuring nonphotochemical quenching (NPQ; Figure 4d) derived from measurements of chlorophyll *a* fluorescence from PSII (Logan et al., 2007; Maxwell & Johnson, 2000). Nonphotochemical quenching refers to excitation energy quenching in PSII by xanthophyll pigment interconversions (Demmig-Adams & Adams, 2006) and the ΔpH gradient across thylakoids (Horton et al., 1994). There were no differences in NPQ as PAR increased when comparing plants grown under WSPVs or clear windows (Figure 4d), so differences in photosynthesis (Figures 4a and 4b) may contribute to growth of roots, or oxidative respiration. For dark-adapted leaves, the quantum yield of PSII (F_V/F_M, Figure 4d inset) was also not different for leaves under clear or dyed windows. These results suggest no differences in PSII function for tomato leaves grown under WSPVs compared to those under clear windows. Omics studies would reveal much about the structure of the photosynthetic apparatus for plants grown under WSPVs in comparison to clear windows (Allen, 2017).

Are these findings about the effects of WSPVs on photosynthesis of tomatoes consistent across other species commercially grown in greenhouses? We have surveyed impacts of growth under WSPVs on photosynthesis in terms of light-adapted energy transfer in photosystem II (ΦPSII), for a variety of crop species grown under plastic panels with luminescent dye and under clear plastic (Table S1, Supporting Information). The measurement of ΦPSII is a robust and rapid assay for surveying photosynthetic responses to light, as it is highly correlated with photosynthetic CO_2 uptake (Krall et al., 1991). Higher values of ΦPSII typically mean greater overall physiological capacity. The effects of the luminescent dye in windows on ΦPSII were neutral for most of the 18 species tested. However, five species (two of three varieties of pepper, key limes, strawberries, and Roma tomatoes) exhibited significantly higher ΦPSII values under the luminescent dye, which is consistent with a higher efficiency of photosynthesis. These differences in the response of PSII highlight the need to better understand how photosynthesis varies across species in response to the altered spectral quality and reduced PAR under the WSPVs. The use of fluorometers or spectrometers could help to develop a more extensive database about which plant species and varieties might be most economically viable for cultivation under WSPVs.

Do plants under WSPVs make the same number or mass of fruits? The initiation and development of plant structures is responsive to the physical environment in which those structures develop, and results in varying number, sizes, shapes, and biomass of plant parts. We have found differences in the response of fruit mass or number of tomatoes per plant after several weeks of growth under luminescent dye: most tomato cultivars (e.g., cv Trust, Figures 4g and 4h) show no differences between dyed and clear windows, though one has slightly fewer and smaller fruit (cv Clarence, Figures 4e and 4f). However, two other species had similar or slightly higher values for fruit number and mass. Overall, characterizing the variation in the effect of growth under WSPVs on number, size, quality, appearance, taste, and nutrition of commercially valuable plant parts should be a high priority for future research.

There is much yet to be learned about the mechanisms that drive plant growth and development under the luminescent dye in WSPVs, particularly with regard to light regulation of gene expression, organogenesis, "source" versus "sink" coördination, and allocation of photosynthetic products to different structures (i.e., roots, stems, leaves, flowers, fruits, and seeds.) We particularly need more systematic studies on responses to WSPVs of various noncrop species, including those with different growth forms (herbaceous versus woody species), phylogenies (dicots versus monocots), life histories (annuals versus perennials), and photosynthetic pathways (C_3, C_4, and CAM carbon fixation pathways).

2. Outlook for the Future

There is tremendous potential for WSPVs to transform electricity generation in many ways. In regions where the surface shortwave radiation interception is high, WSPVs could allow for greater adoption of installed solar electricity generation capacity that is more sustainable in terms of materials, lower in cost, and more efficient than conventional Si-PV cells. Policies that provide incentives to enhance the sustainability of renewable energy technologies should encourage development of new innovations such as WSPVs. For example, the global area under glass and plastic greenhouse cultivation was about 6000 km^2 (about 1.5 million acres) in the mid-1990s and has increased over sixfold over the past 20 years (Wittwer & Castilla, 1995). The use of plastic for greenhouse construction has dramatically increased worldwide, particularly in China, Spain, and Korea (Chang et al., 2013). Plastic greenhouses are easy to manage and rapidly provide economic returns so they are readily accessible for small operations and families, and they provide certain ecological benefits (Chang et al., 2013). Incorporating WSPV technology into both high-tech, large-scale commercial glasshouse operations and the rapidly growing, global trend of plastic greenhouse cultivation would provide additional economic and environmental benefits of low-cost, distributed electricity generation.

WSPVs should help facilitate development of smart greenhouses that maximize energy and water use efficiency while growing food (Li et al., 2017). Precision greenhouse agriculture is not a new field (Cannon, 2017), but WSPVs could help provide power for the new generation of embedded glasshouse sensor networks, controlled by small single-board computers and robotics, and integrated with the Internet of Things (Shaikh et al., 2017).

Deployment of WSPVs for generating electricity in stand-alone settings (i.e., in addition to our current utilization as greenhouse coverings) should be a high priority for research. WSPV solar arrays could be installed *in lieu* of Si-PVs in deserts and other similar open spaces (e.g., grasslands, ranchlands). Conventional solar farms often result in considerable habitat alteration to vegetation and soils (Guerin, 2017); WSPVs may help facilitate restoration of native species populations following site development and facility installation by allowing light for plant growth beneath the infrastructure. WSPVs could be installed over cropland, grazing lands, less-intensively managed grasslands, and desert habitats to enhance the gains accrued from agrivoltaics. Studies should be done to compare the effects of WSPV electricity generation on ecosystem patterns and processes in side-by-side comparisons with Si-PV configured in the same manner. It will be critically important to develop models of the impacts of light quality under the electricity-generating (WSPV versus standard Si-PV) panels on plant recruitment, carbon and water fluxes, Net Primary Production, community composition, and nutrient cycling (Armstrong et al., 2013). Are microsites under WSPVs susceptible to invasion by non-native species? Can they be restored with native species to increase latent energy fluxes to reduce the Photovoltaic Heat Island Effect (Barron-Gafford et al., 2016)? Answers to these questions will allow land managers to make better decisions about when and where to incorporate WSPVs into utility-scale solar testbeds.

Numerous questions remain about the impacts of the light environment below WSPVs on plant growth for commercial crop production management or family home gardens. Results on photosynthetic and photomorphogenetic responses to growth under the dye shows that the transition of WSPVs to commercial use in greenhouse vegetable production will require better understanding of the potential impacts of WSPVs on growth across the huge diversity of crop species. Maximizing production will require more knowledge of how WSPVs affect phylogenetic, life history, and other traits that affect vegetative growth and flower, fruit, and seed production. For example, we have only very superficially examined photosynthetic physiology for a handful of species, and much more work needs to be done to determine how photosynthetic biochemistry and chloroplast structure are affected by the light environment under the luminescent dye used in WSPVs. Likewise, the factors that affect plant development, such as the potential involvement of phytochrome or other photoreceptors such as various cytochromes, cryptochromes, phototropins, and the Zeitlupes, could be matched with the type and concentration of the dye used in WSPVs to better match biological processes with dye absorption, photoluminescence, transmission, and pigment action spectra. For those who manage commercial production operations, efficiency of growth under WSPVs will benefit from better knowledge of effects on C_3, C_4, and CAM photosynthetic pathways; stem versus root versus fruit versus seed crops; monocots versus dicots; woody versus herbaceous species; as well as comparisons between cultivars, varieties, and heirlooms within species. Quantitative studies are also needed on the quality of crops produced under WSPVs, such as fruit shape, color, appearance, and nutritional content.

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