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High-Concentration Photovoltaics for Dual-Use with Agriculture

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Abstract. This study assesses the potential of transparent, tracking-integrated CPV to facilitate more effective dual-use of land for simultaneous agricultural and solar energy production. The concept leverages on the fact that a concentration system is a natural light splitter, separating direct solar radiation from the diffuse. Therefore a transparent CPV module using multijunction solar cells can generate a large supply of electrical power while preserving the diffuse component of sunlight for other uses – in this case, to illuminate crops. We consider the solar resource, the light requirements of plants and the achievable optical properties of the proposed system to evaluate the potential of direct-diffuse light-splitting CPV in agriculture. We show that a tracking-integrated, transparent CPV system integrated into the roof of a greenhouse can provide comparable solar energy generation to a Si solar array, while still admitting sufficient light to cover most of the daily light requirements of many crops.

PHOTOVOLTAICS IN AGRIGULTURE: IMPORTANCE AND IMPLEMENTATIONS

As solar energy from photovoltaics sets pricing records for the electricity sector [1], attention is increasingly turning to how solar energy can be deployed with minimal competition with other land uses. Recent records for solar energy in terms of pricing and scale have been achieved in deserts, where such competition is minimized. As solar energy expands beyond these most favorable settings, competition with other land uses can lead to unintended consequences. In the northern US, developers frequently clear-cut forest in order to make room for solar parks, degrading the natural environment and substantially canceling out the carbon emissions benefit of the solar park by removing carbon-sinking trees [2]. In densely-populated Japan, lack of space has driven solar projects into mountainous areas leading to prices far higher than other regions with comparable solar resource [3]. These challenges have led to rising interest in so-called “agri-photovoltaics,” where photovoltaic energy generation coexists with farming. As both agriculture and electricity generation require sunlight, agri-photovoltaics inherently implies a tradeoff between food and energy production. In Britain, solar installations have provided much-needed revenue to farmers, but at the expense of partially displacing grain, vegetable and fruit crops [4].

These challenges highlight the importance of maximizing solar resource utilization in agricultural PV systems. Substantial effort has gone into developing and testing systems tailored for deployment on agricultural land. Many projects integrating solar energy production and farming have been established in recent years. In pilot-scale tests in Germany, bifacial solar panels mounted above active cropland were shown to produce 80% as much power per unit land area as a traditional photovoltaic plant, while reducing crop yields by between 5 and 20% relative to open farmland, depending on the crops [5]. Tests in Massachusetts have showed that under hot summer conditions, crop growth and yield can actually be improved by growing in the shade of solar panels, especially during hot summers as plants are protected against excessive evaporation and scorching [6]. PV power generation has also been integrated into greenhouse farming by integrating PV cells into the greenhouse roof [7]. Recently, concentrator photovoltaic (CPV) systems have been proposed to give additional flexibility in the division of light between crop growth and power generation. Luminescent solar concentrators have been proposed for integration into greenhouses

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[8], as well as spectrum-selective systems which reflect red and blue light onto farmland and concentrate the remainder onto solar cells [9]. However the optical efficiency of luminescent concentrators remains low, and reflector-based concentrator systems are unable to make use of the diffuse component of sunlight for either agriculture or power generation.

This study evaluates a concept based on a high-concentration CPV configuration, illustrated in Figure 1, where direct light is focused onto small high-efficiency cells and diffuse light is transmitted. In this way the HCPV is used as a natural direct-diffuse light splitter, enabling high power conversion efficiencies while recovering the diffuse component which is typically lost in concentrator systems.

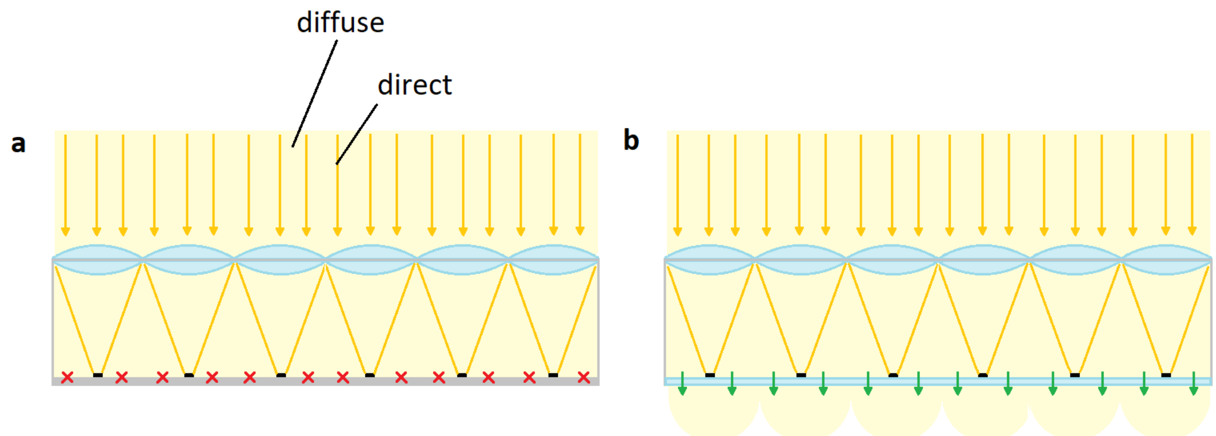

FIGURE 1. Conventional CPV modules block diffuse light (a). The concept evaluated here relies on a transparent module which transmits most of the diffuse component.

MAINTAINING CROP YIELDS: HOW MUCH LIGHT DO PLANTS NEED?

Optimizing a system to divide sunlight between solar cells and plants requires consideration of what the precise light requirements of plants are. Spectrum-selective systems typically leverage on the fact that chlorophyll absorbs most strongly in the red and the blue, with very low absorbance in the green. However, horticulturalists generally consider plants as using the entire visible spectrum (400-700nm) which is referred to in this context as photosynthetically active radiation (PAR). Prior study has demonstrated that the majority of green light is actually absorbed in an optically thick leaf, and contributes significantly to photosynthesis [10]. The relevant spectrum to refer to when considering how to weight different wavelengths of light is not the absorbance spectrum of chlorophyll but rather the action spectrum of a particular species of plant, which represents the relative rate of carbon fixing under illumination by different wavelengths. These spectra typically show the highest photosynthetic action in the red with a secondary peak in the blue [11]. While the mid-visible contributes somewhat less photosynthetic action, its contribution to photosynthesis is significant and cannot be ignored.

The principle measure of plant light requirements is the daily light integral (DLI), or the total amount of PAR that falls on the plant during the day, measured in moles of photons (mol_{PAR}). DLI requirements of plants vary widely, but are typically categorized as low-light (<10 mol_{PAR}/m^2/day), moderate-light (10-20 mol_{PAR}/m^2/day), high-light (20-30 mol_{PAR}/m^2/day), and very high-light (>30 mol_{PAR}/m^2/day) [12]. The CPV concept explored here aims to supply most of the plant light requirements from the diffuse component of the solar resource. Based on standard spectra and meteorological data, we consider the potential of the solar resource in one of our target locations to meet this goal. A conversion factor to obtain PAR from full spectrum irradiance data in W/m^2 and photon flux can be calculated by integrating the visible portion of the photon flux spectrum over the full-spectrum irradiance:

$$C_{PAR} = \frac{\int_{400}^{700} \varphi(\lambda)\mathrm{d}\lambda}{\int_0^{\infty} I(\lambda)d\lambda} \tag{1}$$

where $\varphi(\lambda)$ is the incident spectrum in terms of photon flux, and $I(\lambda)$ is the spectrum in W/m^2. Using NREL's AM1.5 reference spectra, we calculate conversion factors from total solar irradiance to PAR flux for both the global and diffuse components. Applying Eq. 1 we derive the conversion factors (in μmol of PAR photons/second per Watt of solar radiation):

C_{PAR} global: 1.97 $\mu mol_{PAR}\ s^{-1} / W_{solar}$
C_{PAR} diffuse: 2.42 $\mu mol_{PAR}\ s^{-1} / W_{solar}$

Applying these conversion factors to hourly TMY2 solar irradiance data for two locations, Abu Dhabi, UAE and Worcester, Massachusetts USA, in January and July, we compute the DLI obtained from the diffuse component on a typical clear day, displayed in Figure 2. In both the subtropical desert location of Abu Dhabi and the temperate climate of Massachusetts, the wintertime diffuse radiation delivers a sufficient DLI for low-light plants. The summertime diffuse DLI in Abu Dhabi can support moderate-light crops, while the longer summer day of Massachusetts delivers a DLI in the high-light range.

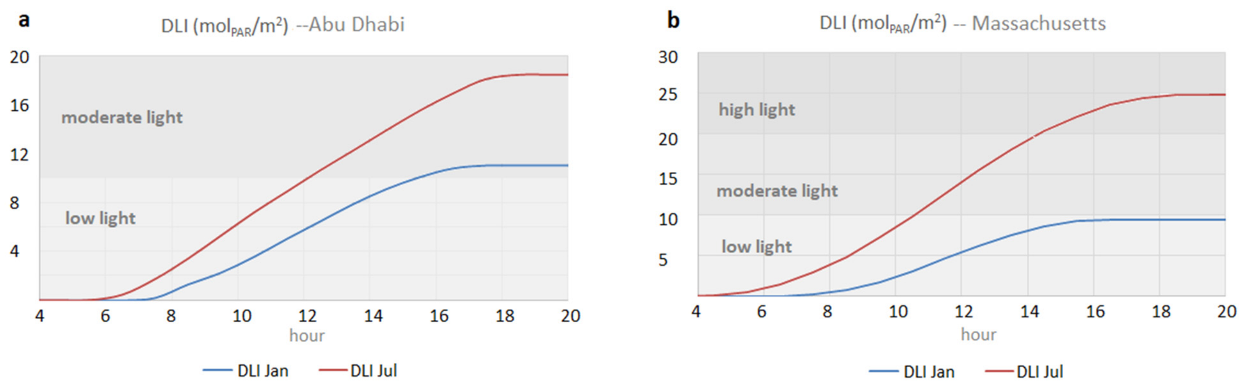

FIGURE 2. Estimated daily light integral from the diffuse component only, on typical clear days in January and July for a) Abu Dhabi, UAE and b) Worcester, Massachusetts USA.

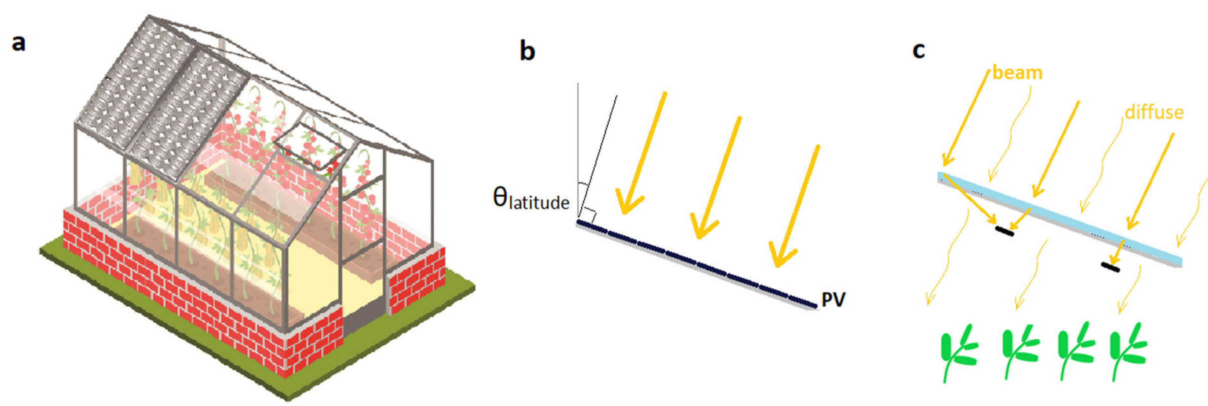

FIGURE 3. a) We evaluate the potential for tracking-integrated, semi-transparent CPV installed in greenhouse roofs. We compare the simulated performance of b) a 16% efficiency PV array applied to the greenhouse roof at latitude tilt and c) the estimated output of a 30% direct efficiency, diffuse-transparent CPV array.

TEST CASE: THE CPV GREENHOUSE

How much of this DLI will be available to a realistic system? We attempt to obtain an approximate answer for the specific case of transparent, tracking-integrated CPV system incorporated into the roof of a greenhouse. The concept is illustrated in Figure 3a. Our assessment of the concept is "technology-agnostic" – we do not specify a specific optical design or tracking mechanism. Rather we specify certain realistic parameters relating to the optical properties of the module and estimate the power generated and DLI transmitted. We vary the tracking range from

±70° (which can capture nearly all of the daily solar resource) to ±40°, to account for the difficulty of achieving full-day tracking in most tracking-integrated systems [13].

The system is modeled as a rooftop system at latitude tilt using SAM. An initial baseline simulation is done using 16% efficient Si solar panels in a system with a nominal capacity of $9kW_p$. The summer, autumn and winter daily DC power output are modeled for the PV system under Massachusetts conditions, as well as the direct and diffuse plane of array irradiance. The CPV system performance is estimated by assuming a 30% conversion efficiency of the direct component during all hours when the incidence angle of direct sunlight on the module falls within the tracking range of the integrated sun tracking system. In keeping with previous tests of semi-transparent CPV prototypes [14], we consider that 70% of the diffuse component will be transmitted through the module. When the sun falls outside of the tracking range, we further assume that 50% of the direct component will be transmitted as well, with significant loss expected due to strong Fresnel reflections at the optical interfaces.

Figure 4a-c displays the cumulative power output from the Si reference system (computed in SAM) and the CPV system (estimated from hourly irradiance data by the method described above) with 40°, 50° and 70° tracking range. Figure 4d-f show the daily light integral transmitted through the rooftop for the modeled CPV systems with different tracking ranges, under the optical properties assumed above.

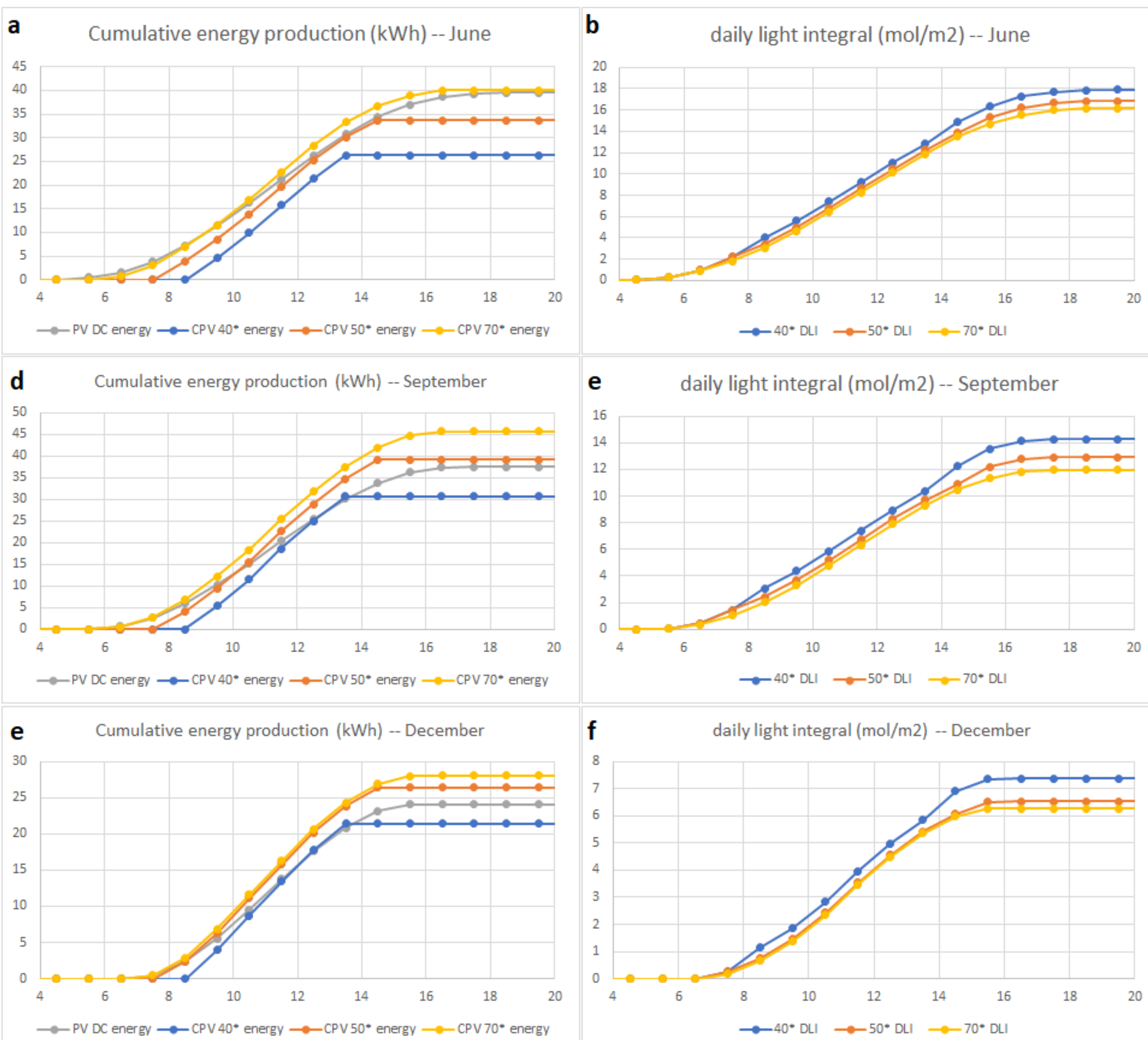

FIGURE 4. Estimated CPV output assuming 30% power conversion of direct solar component within the tracking range, and transmitted PAR daily light integral assuming 70% transmission of diffuse and 50% transmission of direct incident outside of the tracking range. Based on TMY2 solar resource data for Worcester, MA.

We note that the DLI values shown refer to the PAR that is transmitted through the areas of the roof that are covered by CPV. In a real setting, additional light will be admitted through the sides and uncovered roof area. Also noteworthy is the fact that these results are expected in a mid-DNI region where CPV is not generally seen as viable. By treating the unconcentrated diffuse radiation as a resource rather than a loss, the light-splitting concept has the potential to make CPV useful beyond its traditional range of high-DNI desert environments. This concept is envisioned to have particular use in offsetting energy requirements in greenhouse settings where significant climate control is required; in addition we anticipate applications beyond the field of agriculture in other setting, in particular building integration, where both high power output and high optical transmittance are required.

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