Design Considerations for Agrophotovoltaic Systems: Maintaining PV Area with Increased Crop Yield

Allison Perna, Elizabeth K. Grubbs, Rakesh Agrawal, Peter Bermel

Purdue University, West Lafayette, IN, 47907, USA.

***Abstract* — Land use constraints have motivated investigation into the spatial coexistence of photovoltaics and agriculture. Existing experimental work has emphasized fixed south-facing configurations with traditional commercial panel shapes, and modeling work is sparse. Previous work also concludes that agriculture-photovoltaic (agrophotovoltaic) systems either decrease crop yield or are limited to shade-tolerant crops. In this work, we explore the effects of different PV array configurations and panel designs on field insolation. We find that east-west tracking configurations outperform fixed south-facing configurations due to shadow migration paths. Additionally, we show through optical modeling that utilization of mini-modules in patterned panel designs may create more optimal conditions for plant growth while using the same area of PV, thus improving the land-use efficiency of the agrophotovoltaic system.**

***Index Terms* — aglectric, agrophotovoltaic, agrivoltaic, photovoltaics, agriculture.**

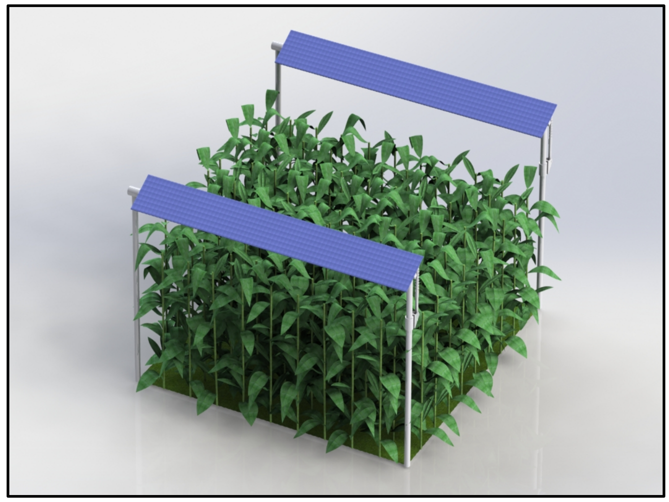

Fig. 1. Schematic of a portion of an agrophotovoltaic east-west tracking system for late-season maize.

I. Introduction

In recent years, land use constraints and a desire for increased land use efficiency have motivated initial explorations into coproduction of electricity and agriculture on the same land in so-called “aglectric” systems [1]. To this end, implementation of wind energy production on pastureland is well known, while incorporation of photovoltaic arrays on cropland is less well explored [1]. In the push for increased solar deployment, it is found that electricity production self-sufficiency at the state level in the U.S. is not achievable without impeding on land dedicated to agriculture [1]. This is due to the dilute nature of solar energy, which results in production of 4-11 W/m^2 in typical U.S. solar arrays, averaged over a whole year [1]-[2].

This concept of solar and agriculture coexistence has been proposed in various forms over the past few decades [3]-[5]. However, most of this work discusses implementation of existing panel designs or is limited to shade-tolerant crops, which are only a small subset of commercial crops. Marrou (2013) found that while agrophotovoltaic systems show promise without major changes to agricultural methods, loss of solar radiation on crops is the major factor that reduces crop yield and therefore mitigating insolation reduction should be the focus of future agrophotovoltaic work [3]. They additionally suggest that shade-tolerant crops be the focus of these systems. The Fraunhofer Institute has implemented various agrophotovoltaic farms. Notably, they reported an absolute increase of 60% in land use efficiency, where 80% of typical yield and 80% of typical electricity was produced in their agrophotovoltaic system for the same land area [4].

Modeling of potential agrophotovoltaic systems is sparse. It was determined in 1982 that elevated (2m) fixed south-facing arrays with 6m row width can produce a nearly spatially homogenous field insolation with a roughly one-third shadowing, compared to an open field case [6]. However, this work does not predict the effects of different dimensions, configurations, or panel designs, limiting its applicability. Fixed south-facing agrophotovoltaic systems have been modeled for the purpose of increased land use efficiency (up to 73%) [7]. Though promising for increasing net land productivity, this goal could threaten global food production if current agricultural productivity and land coverage do not increase accordingly.

To maintain global agricultural yields while increasing renewable electricity production, we developed a model that allows for multiple configurations and geometric panel designs to be explored. To mitigate insolation reduction as suggested in [3], we explore how array configuration and panel designs suggested in [1] influence field insolation.

II. Modeling Approach

To address this problem accurately, we developed a ray-tracing model using MATLAB that utilizes the open-source library PVLib to create a spatial map of insolation integrated over a single day [8]. This model treats the sun as a plane

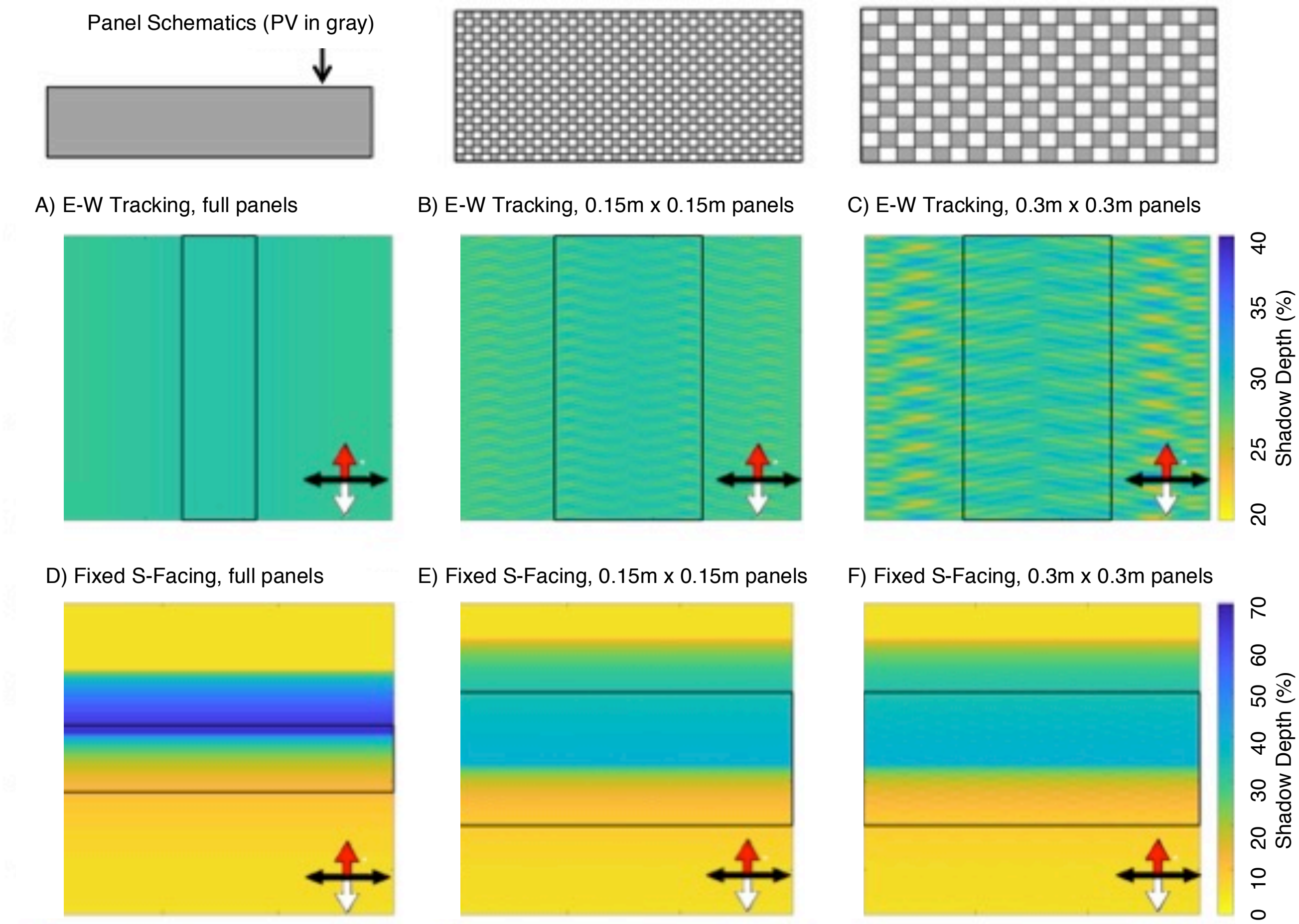

Fig. 2. Shadow depth (reduction in insolation integrated over a single day) top-down spatial plots for east-west tracking (a-c) and latitude-tilt fixed south-facing (d-f) systems in Fresno, CA. Plots show a single unit cell for simulations of infinite periodicity in both areal dimensions. Field dimensions are 6m x 7m. Row width is 7m. Panel width is 1.5m for (a) and (d), and is 3m for (b-c, e-f); panels modeled are shown above with their outline overlaid on the spatial insolation distribution plots. Total photovoltaic area is conserved across systems. East-west tracking configurations show superior homogeneity compared to fixed south-facing configurations, suggesting potentially improved yields for many commercial crops.

source and finds the corresponding positions of direct light rays in the field in the two areal dimensions using finite elements. The only light-intercepting structures modeled are the PV panels, which are treated as rectangular planar segments with zero thickness. Shadow positions are calculated from sunrise to sunset using the apparent solar elevation from each corner of the panel at each time step, as calculated using PVLIB. The line drawing algorithm from MATLAB's poly2mask function maps shadow locations in a binary fashion in the finite element matrix representing the field. 100% of direct light is removed from each of these shadowed elements for that particular timestep. This method creates harsher lines than would be observed in reality but is reasonable for our purposes. Spatial grid parity was achieved using spatial elements of size 0.01m x 0.01m, and the temporal resolution for our simulations is 1 min. Infinite periodicity is implemented to eliminate statistical error from edge effects. For the systems simulated in this paper, panels are infinitely long and an infinite number of panel rows with a row width (defined as the distance between the central axes of each panel row) of 7m (Fig. 2, Table 1) or 7.62m (Fig. 3) are simulated.

For east-west tracking systems, the single axis tracking function from PVLIB was used with backtracking off. South-facing systems were modeled at latitude-tilt (36.6 degrees from the horizontal for Fresno, CA and 33.8 degrees from the horizontal for the South Plains region of Texas).

To model irradiance, we implemented the Haurwitz clear sky model and the Orgill and Hollands model as implemented by PVLIB for decomposition into diffuse and direct components. These values were normalized by NASA monthly averages from 22-year metrological data to avoid overestimation of insolation when estimating crop yield [9]. Diffuse light is assumed to be homogenous across the field, as

TABLE I

SHADOW DEPTH AND SHADOW DURATION DATA

Systems (in Fresno, CA)	Shadow Depth (%)	Shadow Duration (min)	
	Spatial Average and Standard Deviation	Midday (10AM – 4PM) Average and Standard Deviation	Full day Average and Standard Deviation
A) East-west tracking, full panels	28.9 ± 0.4	69.7 ± 2.6	71.3 ± 1.5
B) East-west tracking, 0.15m x 0.15m checkerboard panels	28.6 ± 1.0	9.8 ± 2.9	40.6 ± 9.1
C) East-west tracking, 0.3m x 0.3m checkerboard panels	28.6 ± 1.5	15.8 ± 3.7	38.6 ± 8.6
D) Fixed south-facing, full panels	18.8 ± 19.3	67.1 ± 126.4	98.1 ± 128.4
E) Fixed south-facing, 0.15m x 0.15m checkerboard panels	18.8 ± 13.1	4.4 ± 4.8	16.6 ± 3.1
F) Fixed south-facing, 0.3m x 0.3m checkerboard panels	18.8 ± 13.1	7.4 ± 8.0	17.1 ± 3.1

is calculated in [6], and is estimated as the fraction of diffuse light remaining after modeling incident light on the PV plane using the Perez model at each time step. For our simulated structures, this yields a roughly 10% decrease in diffuse light throughout the day. All simulations on this paper were conducted using solar positioning and irradiance models for June 1, 2018.

III. RESULTS AND DISCUSSION

The effects on field insolation from various photovoltaic array configurations and panel designs were simulated. To estimate viability, we examined the net photosynthetic rate of major agricultural crops as a function of incident irradiance. Major agricultural crops in the U.S. undergo one of two major photosynthesis types: C3 or C4. As distinct metabolic pathways, they experience different utilization of resources such as water, CO_2, and photosynthetically active radiation (PAR). In the case of C3 plants, the photosynthetic rate generally saturates at lower levels of irradiance. This trait suggests that redirecting the irradiance of crops for electricity production may not affect crop yield, which is corroborated by our collaborators at Purdue's Department of Agronomy [10]. More complex crop models and experimental work is needed to determine true viability, therefore we have checked our model with existing experimental implementations for array configuration. No existing experimental work exists on the effects of manipulating the PV panel design.

The major agricultural regions of Fresno, California (36.6, -119.9) and the South Plains region of Texas (33.5, -101.8) have promising characteristics for agrophotovoltaic systems. Their high summer irradiance exceeds saturation irradiance of major regional C3 crops (cotton in TX and rice in CA, with saturation irradiance of ~1300 μmol m^{-2} s^{-1} PAR [11]-[12]). This value corresponds to ~650 W m^{-2} of the full AM1.5 spectrum, which is significantly lower than the average midday irradiance for both locations during the summer growing season for many major crops, suggesting redirection of part of the solar spectrum in these regions may not negatively affect crop yield [9]-[10].

However, there are multiple other requirements for maintaining crop yield. For field crops, homogeneity of insolation reductions is crucial for most farming practices. Additionally, the duration of direct shadows during periods of low irradiance (near sunrise and sunset) may push plants into low photosynthetic rate regimes, or possibly into respiratory regimes, which can negatively impact plants [10]. The systems we modeled take these considerations into account.

For our analysis, we define the term 'shadow depth' as the percent reduction in energy from solar radiation incident on the field integrated over the 24-hour day, which is calculated for each finite element in the simulated field. Shadow durations are defined as the length of time a given finite element in the simulated field is under direct shadow.

A. Array Configuration

It is found that PV array configuration is of utmost importance to agrophotovoltaic system viability. Traditional fixed south-facing arrays produce regions of high shadow depth, dubbed shadow 'trenches,' which can reach upwards of 60% when integrated over a single day (Fig. 2, Table 1). Standard deviation of shadow depth is a marker of insolation homogeneity; we calculated high values (>13%) for south-facing systems (Table 1, d-f) and negligibly low values (<2%) for east-west tracking systems (Table 1, a-c). This pattern is expected due to the east-west nature of diurnal shadow migration, and may explain the decreased yield of agrophotovoltaic systems that implemented south-facing structures [4]. Marrou (2013) detected, in experimental south-facing agrophotovoltaic systems, high spatial variability and a decrease of nearly half of available sunlight for high-density systems. Additionally, east-west tracking systems with traditional fully opaque panels have low shadow durations lasting for approximately an hour in midday (10AM – 4PM), compared to south-facing which create shadows lasting multiple hours in the shadow trenches during midday. These high duration midday shadows create the shadow trenches that are detrimental to crop yield, further supporting that north-south axis PV configurations will improve agrophotovoltaic systems.

B. Panel Design

We explored different geometric panel designs for both east-west tracking and fixed south-facing configurations, specifically checkerboard patterns of square mini-modules alternating with air gaps while maintaining the same photovoltaic area (Fig. 2, Table 1). Wider panels with this checkerboard design (Fig. 2 (b-c, e-f), Table 1 (b-c, e-f)) greatly decrease shadow durations. For east-west tracking systems, this reduction is observed across the entire field. For south-facing systems, both the shadow depth and shadow duration in the shadow trench region are reduced significantly. Both results stem from diurnal east-west shadow migration pathways. Though we calculate improved metrics for south-facing systems by implementing checkerboard design, east-west tracking systems still show more favorable properties.

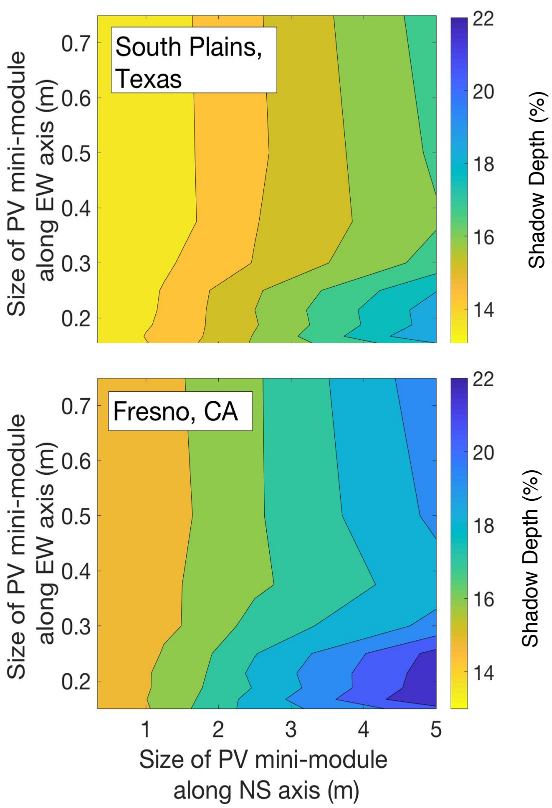

Fig. 3. Maximum shadow depth (%) for varied mini-module dimensions in a checkerboard panel design for east-west tracking configuration. NS axis dimension is more impactful than EW axis dimension. Row width is 7.62m. Panel width is 1.5m. Similar trends are expected for different row widths and panel widths.

We explored the effects of the checkerboard design further in east-west tracking systems by varying the mini-module dimensions (Fig. 3). We demonstrate that, while power production will correspondingly vary, shadow depth can be manipulated by varying the photovoltaic module dimensions and total area. It is also demonstrated that regions with smaller fractions of diffuse light (Fresno, CA) are more impacted by agrophotovoltaic system shadowing effects. By using smaller modules, dimensions 1m by up to 0.8m (Fig. 3), spaced in a checkerboard pattern, maximum irradiance reduction can be reduced by an absolute 6% compared to long module designs.

It is found that the same area of PV can be manipulated to increase homogeneity and thus significantly decrease the maximum irradiance reduction experienced anywhere in the field. Furthermore, it is found that manipulating the PV area can decrease shadow durations over any given plant in the field, suggesting that crops may continuously operate in their peak photosynthetic regime.

IV. Conclusions

In this work, we have found via optical modeling that PV array configuration and panel design have an extremely substantial influence on the homogeneity of field insolation in agrophotovoltaic systems. North-south axis systems, (e.g. east-west tracking systems), are preferable over fixed south-facing systems due to increased insolation homogeneity and decreased shadow duration. Utilization of mini-modules in a checker pattern in these systems increases homogeneity, thus decreasing the maximum field insolation reduction. We conclude that increased PV area does not linearly correlate with decreased expected crop yield; in other words, agrophotovoltaic systems can be optically designed to optimize power output and expected crop yields. Future work will consider this optimization and implement preferred designs in an experimental agrophotovoltaic plot. Progress in these areas will help pave the way towards widespread implementation of agrophotovoltaic systems to increase solar deployment and address land use constraints.

Acknowledgment

The authors thank Shelby Gruss, Val Zayden Schull, Sylvie Brouder, Mitch Tuinstra, and Margaret Gitau for valuable discussions. They also acknowledge research support from the National Science Foundation under Award Nos. EEC-1454315 and EEC-0228390, and from the DOD/United States Navy/Office of Naval Research (ONR) under Award No. N00014-15-1-2833.

References

[1] C. Miskin, Y. Li, A. Perna, R. Ellis, E. K. Grubbs, P. Bermel, R. Agrawal, "Sustainable coproduction of food and solar power to relax land use constraints," *Nature Sustainability*, (submitted, under peer review).

[2] Ong, S., Campbell, C., Denholm, P., Margolis, R. & Heath, G. "Land-use requirements for solar power plants in the United States." No. NREL/TP-6A20-56290. National Renewable Energy Laboratory, 2013.

[3] H. Marrou, L. Guilioni, L. Dufour, C. Dupraz, J. Wéry, "Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels?" *Agriculture and Forest Meteorology*, vol. 177, pp. 117-132, 2013.
[4] Fraunhofer Institute for Solar Energy Systems. "Harvesting the Sun for Power and Produce –Agrophotovoltaics Increases the Land Use Efficiency by over 60 percent." Fraunhofer ISE Press Release (November 23, 2017). https://www.ise.fraunhofer.de/en/press-media/press-releases/2017/harvesting-the-sun-for-power-and-produce-agrophotovoltaics-increases-the-land-use-efficiency-by-over-60-percent.html
[5] H. Dinesh, J. M. Pearce, "The potential of agrivoltaic systems," *Renew. Sust. Energy Rev,* vol. 54, pp. 299-308, 2016.
[6] A. Goetzberger, A. Zastrow, "On the coexistence of solar-energy conversion and plant cultivation," *Int. J. Solar Energy,* vol 1, pp. 55-69, 1982.
[7] Dupraz, C. *et al*. "Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes," *Renew. Energy,* vol. 36, pp. 2725-2732, 2011.
[8] Sandia National Laboratory, PV_Lib Toolbox, 2018.
[9] NASA Langley Research Center, POWER project data sets, 2018. https://power.larc.nasa.gov/
[10] Communication with Jeffrey J. Volenec, 2018.
[11] S. Jose, "Agroforestry for ecosystem services and environmental benefits: an overview." *Agroforestry systems*, vol. 76(1), pp. 1-10, 2004.
[12] Z-P Ye. "A new model for relationship between irradiance and the rate of photosynthesis in oryza sativa," *Photosynthetica,* vol. 45 (4), pp. 637-640, 2007.