Crop-Specific Optimization of Bifacial PV Arrays for Agrivoltaic Food-Energy Production: The Light-Productivity-Factor Approach

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***Abstract*—Agrivoltaics (AV) is an emerging technology having symbiotic benefits for food-energy-water needs of the growing world population and an inherent resilience against climate vulnerabilities. An AV system needs to balance the sunlight sharing between the solar panels and crops to maintain the desired food-energy yields, subject to appropriate constraints. Given the emerging diversity of monofacial and bifacial farms, the lack of a standardized crop-specific metric (to evaluate the efficacy of the irradiance sharing) has made it difficult to optimize/assess the performance of AV systems. Here, we introduce a new metric—light productivity factor (LPF)—that evaluates the effectiveness of irradiance sharing for a given crop type and photovoltaic (PV) array design. The metric allows us to identify optimal design parameters including the spatial PV array density, panel orientation, and single axis tracking schemes specific to the photosynthetically active radiation needs of the crop. By definition, LPF equals 1 for PV-only or crop-only systems. The AV systems enhances LPF between 1 and 2 depending on the shade sensitivity of the crop, PV array configuration, and the season. While traditional fixed-tilt systems increase LPF significantly above 1, we find LPF is maximized at 2 for shade-tolerant crops with a solar farm based on single axis sun tracking scheme. Among the fixed tilt systems, east/west faced bifacial vertical solar farms is particularly promising because it produces smallest variability in the seasonal yield for shade sensitive crops, while providing LPF comparable to the standard N/S faced solar farms. Additional benefits include reduced soiling and ease of movement of large-scale combine-harvester and other farming equipment.**

***Index Terms*—Agrivoltaics, farm productivity, food-energy yield, tracking, vertical bifacial.**

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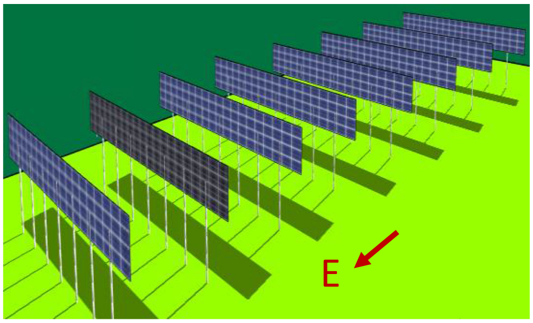
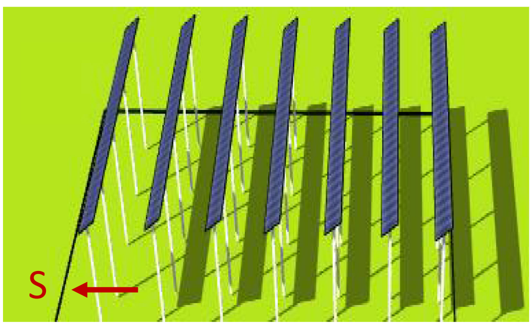
I. Introduction

Along with many positive aspects of rapidly growing photovoltaic (PV) installations, the rapid growth of ground mounted PV farms raises important environmental concerns including the land use conflict with agriculture, adverse impact on ecosystem processes, and loss of biodiversity [1]–[3]. Minimizing these environmental challenges is crucial for the desired techno-ecological growth of PV for increasing world population especially in regions that are highly susceptible to heat stress, drought, and climate change [1]. Recently, an innovative approach of agrivoltaics (AV) farming in which PV and agriculture are collocated has been demonstrated that offers a range of symbiotic benefits including dual food-energy production, reduced water budget, and resistance to climate effects such as excess heat and drought [4]–[8].

Unlike a PV-only or crop-only farms, AV farms are seldom optimized for a specific metric [e.g., levelized cost of electricity (LCOE)]; instead, one adopts an empirical design-of-experiment approach to study the overall farm yield at a given location. A review of the existing AV systems shows that the PV arrays are typically installed 4 to 7 m above the crop level and at a lower density to reduce shading and improve sunlight-sharing between PV modules and crops. There have recently been several field experiments and some modeling studies to assess AV approach for a range of crops including lettuce, wheat, corn, tomatoes, cucumber, and peppers under standard and reduced spatial density of PV arrays [4], [8]–[13]. These initial studies predict that although crop yield can vary under the partial shading of an AV farm as compared to that in open farm, AV yields are not reduced significantly and, in some cases, can even exceed to that in open farm when the array density is carefully selected. Moreover, it has been proposed that cumulative radiation available for crops could be best manipulated through dynamic tilt control of PV panels through custom tracking schemes [13]. Marrou *et al.* [11] showed that the change in the intensity of radiation with respect to open farm condition is the dominant factor for the relative crop yield in an AV farm, although other microclimate parameters, such as the temperature and humidity, may also vary under the AV shades [14], [15]. In essence, although the importance of managing the sunlight balance between solar modules and crops is well-established, there is no systematic approach to *a priori* optimize its design.



(a)



(b)

Fig. 1. (a) E/W faced vertical panels. (b) N/S faced panels at an optimal fixed tilt.

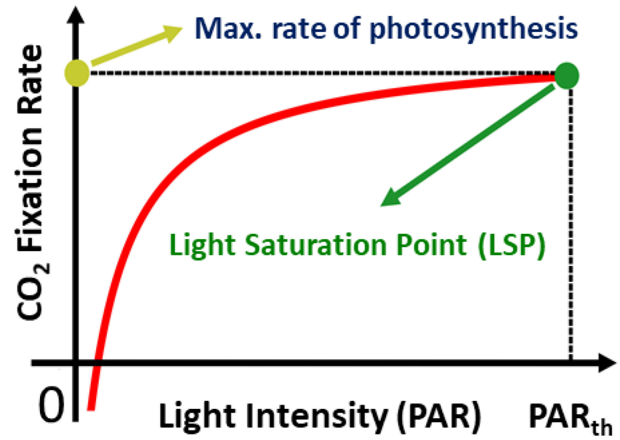


Fig. 2. Typical response of the rate of photosynthesis as a function of sunlight intensity.

Any systematic approach for design optimization must rely on a metric to characterize the farm productivity for a given balance of sunlight between PV modules and crops. Unfortunately, the community is yet to define a suitable metric that can be used *in the design phase*. For example, in a simple approach, the sunlight sharing in AV could be characterized by the amount intercepted by the panels and the photosynthetically active radiation (PAR) available to the crops under the PV arrays. Recently, Hussnain *et al.* [10] explored the relative performance of N/S faced fixed tilt PV arrays versus E/W faced vertical bifacial PV arrays (see Fig. 1) based on this simple sunlight sharing model. While this method is simple, incident PAR under panels is a crop-independent parameter and cannot be used for a crop-specific optimization. On the other hand, sophisticated mechanistic crop models have been used to predict the crop yield as a function of shading as well as other parameters [6], [9]. The physiological response of crops in AV systems is, however, a topic of active research and the validity of various mechanistic crop models under artificial shading of solar modules await field validation [16]. A simpler yet crop-specific approach would facilitate to optimize the design of AV solar arrays and the choice of suitable crops.

In this article, we introduce a crop-specific metric that can indicate potential AV performance for a given PV array design. The approach is based on evaluating how an AV system alters the availability of useful PAR (PAR_u) at the crop level, as compared to that in an open farm. The PAR_u is the daily integrated PAR that contributes to the crop's photosynthesis process. It is well-known that the rate of photosynthesis in plants increases with the PAR intensity up to a certain threshold value, which is known as the light saturation point or threshold PAR (PAR_{th}), see Fig. 2. Increasing PAR intensity above PAR_{th} does not increase the photosynthesis rate. For AV systems, it is, therefore, useful to evaluate how the shading under the panels varies the PAR_u across various seasons for a given crop. When PAR_u is combined with the intercepted solar irradiation by the solar modules, net productivity of sunlight for food-energy can be obtained. We quantify this in terms of a new metric called the light productivity factor (LPF). As a correlated metric to experimentally reported metric known as the land equivalent ratio (LER) (which indicates food-energy performance based on the *measured* crop yield and the PV output), LPF would enable a crop-specific optimization of the PV array density, orientation, and the mobile tilt algorithms at the design phase. Using this approach and as an illustrative example, we evaluate various AV design configurations for Lahore (31.5204° N, 74.3587° E) using typical meteorological data. In particular, we explore the following:

1) farm productivity for fixed tilt bifacial PV arrays that include the standard N/S faced optimally tilt panels versus E/W faced vertical bifacial panels;
2) farm productivity for the standard versus nonstandard single axis tracking schemes using bifacial panels;
3) crop dependence and seasonal variations in the farm productivity for fixed and mobile tilt PV systems;
4) performance evaluation of various PV array configurations for a given constraint on the crop yield.

Three representative crops, i.e., lettuce, turnip, and corn are considered to cover a broad range of PAR_{th} while a variety of monofacial and bifacial panel configurations are explored to illustrate the relative design tradeoffs. Although other practical considerations such as the required elevation of the arrays for farm machinery movement, climatic stresses on crops, and soiling power loss can influence the choice of a suitable PV array design for agrivoltaics, here we will focus exclusively on the food-energy productivity of the farm for unstressed crops. The rest of the article is organized as follows. In Section II, we describe in detail the modeling methodology. Simulation and modeling results are discussed in Section III. Finally, Section IV concludes this article.

II. Modeling Approach

A. Integrated Model for PV Energy Yield and PAR

A 2-D model, appropriate for typical large scale commercial farms arranged in very long rows, is used to compute the solar irradiance interception along the height of the panels, the generated PV energy, and the incident PAR under the panels as a function of space and time per unit farm area. The length of the PV rows and the total number of rows are assumed large so that edge effects and variations along the dimension of PV rows are negligible. The 2-D model can accurately predict the system performance (except close to the edges) with a much-reduced analytical complexity as compared to 3-D approach [17].

The details of the analytical 2-D model have been reported elsewhere [10]. Briefly, the solar irradiance is evaluated as a function of time during the day for the location specified by its latitude and longitude using Sandia's PVLib library [18] to calculate the Sun's zenith and azimuth angles. The Global Horizontal Irradiance (GHI) is first calculated using Haurwitz clear sky model implemented in PVLib and is then renormalized based on the typical meteorological data from NASA Surface meteorology and solar energy database [19]. The GHI is then split into direct normal irradiance and diffuse horizontal irradiance using Orgill and Hollands model [20].

To compute the PV energy and incident PAR underneath the PV arrays, the spatial-temporal interception of the direct and diffuse sunlight along the height of panels and along horizontal plane underneath the PV arrays is evaluated using the view factors approach [10], [21]–[23]. The albedo collection at the panels is similarly modeled. An accurately implemented view factor approach can provide a similar accuracy as that of the ray-tracking approach, but at a much-reduced computational cost [32], [33]. The approach has been validated with published field data for both standard and AV farms [10], [21]. The overall modeling framework is illustrated in Fig. 3.

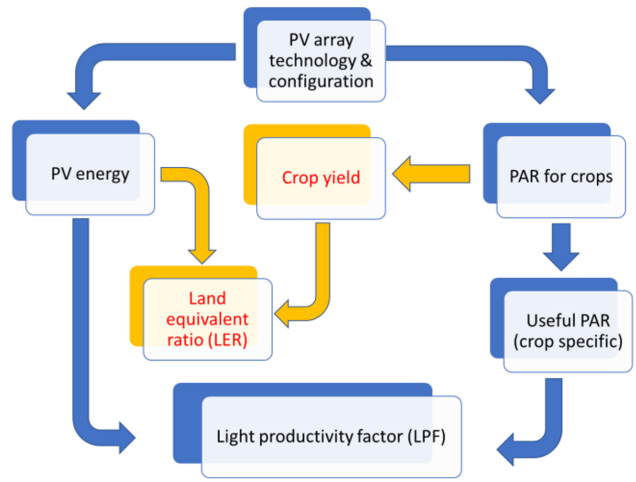


Fig. 3. Comparison of the modeling frameworks based on PAR, LER, and LPF approaches. The yellow and blue blocks highlight the difference in the standard (LER) approach versus the LPF approach used in this article, respectively.

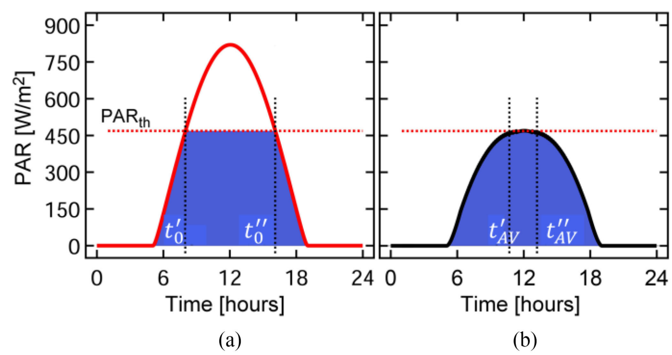


Fig. 4. PAR incident on the crop across a day for open farm (left) and under full density PV array (right). t'_0 and $t''_0$are the times at which the incident PAR exactly matches to PAR_{th} in the morning and the afternoon, respectively, for an open farm, while t'_{AV} and t''_{AV} are the times at which the incident PAR exactly matches to PAR_{th} in the morning and the afternoon, respectively, for AV farm.

B. PV Array Configurations

The farm productivity is analyzed for PV arrays with varying spatial density measured relative to optimized PV-only farm. Full (standard) array density is defined when row-to-row pitch (p) is twice as that of the panel row width (h), i.e., $p/h = 2$. Similarly, half-density farm is defined by $p/h = 4$. Alternatively, full and half densities can be defined in terms of the ground coverage ratio ($\mathrm{GCR} = h/p$) of 1/2 and 1/4, respectively. For the performance comparison, the tracking schemes are compared with fixed-tilt N/S facing monofacial and E/W facing vertical bifacial farms. The definitions of full and half densities of PV arrays are taken from standard AV literature.

For sun-tracking tilt, single axis tracking for the E/W facing bifacial PV modules is considered with various tracking schemes. The standard tracking (ST) scheme is defined when modules are oriented normal to direct sunbeam. On the other hand, for reverse/antitracking (RT) scheme, modules are oriented parallel to the direct beam. For RT, although direct light shadowing is absent, the diffused sunlight under the panels is partially blocked and the overall PAR intensity is lower compared to the open farm. The customized tracking (CT) scheme switches between ST around noon and RT closer to sunrise and sunset. It implements ST for n number of hours symmetrically before and after the midday. For other times during the day, RT is implemented.

C. Useful PAR Yield and Light Productivity Factor

It is well established that each crop has a threshold PAR, PAR_{th}, above which the photosynthesis rate saturates [27], [28]–[31]. The PAR available to the crops reduces under PV arrays as a function of the array density and the mobile tilt algorithm.

For open farm and clear sky conditions, the time varying PAR (PAR_0) can be expressed as

$$\mathrm{PAR}_o\,(t) \tag{1}$$

$C_{AM1.5} \times \text{GHI}\ (t)$ where $C_{AM1.5} \approx 0.51$ is the ratio of the integrated PAR (400 nm–700 nm) to the integrated global standard (*AM*1.5g) sunlight spectrum. For an AV system, the spatially average, time varying PAR on a horizontal plane at any height under the panels can be evaluated as

$$\text{PAR}_{\text{AV}}\ (t)\ = C_{AM1.5}\ \times\ (\text{GHI}\ (t) -\ G_{\text{PV}}\ (t)) \quad (2)$$

where G_{PV} is the sum of spatially averaged direct and diffused irradiation on a horizontal plane that is blocked by solar modules, respectively.

By integrating the time-varying PAR over the entire day while imposing an upper limit of PAR_{th} for a given crop, we can obtain a crop-specific useful daily PAR (see Fig. 4):

$$\text{PAR}_{u,\ \text{open}} = \int_{t_r}^{t_0'} \text{PAR}_0\ (t)\ dt + \int_{t_0''}^{t_s} \text{PAR}_0\ (t)\, dt + (t_0'' - t') \times \text{PAR}_{th} \quad (3a)$$

$$\text{PAR}_{u,\text{AV}} = \int_{t_r}^{t_{\text{AV}}'} \text{PAR}_{\text{AV}}\ (t)\ dt + \int_{t_{\text{AV}}''}^{t_s} \text{PAR}_{\text{AV}}\ (t)\, dt + (t_{\text{AV}}'' - t_{\text{AV}}') \times \text{PAR}_{th} \quad (3b)$$

where $\text{PAR}_{u,\text{open}}$ and $\text{PAR}_{u,\text{AV}}$ are daily useful PAR for open farm and under solar panels, respectively, t_r and t_s are the sunrise and sunset times, respectively, $t_0'(t_{\text{AV}}')$ and $t_0''(t_{\text{AV}}'')$ are the times at which $\text{PAR}_0(\text{PAR}_{\text{AV}})$ exactly matches to PAR_{th} in the morning and the afternoon, respectively. For the case when PAR_{th} remains higher than $\text{PAR}_0(\text{PAR}_{\text{AV}})$ across the day, t_0', t_{AV}', t_0'', and t_{AV}'' are defined to be the peak sunlight time. PAR_{th} for lettuce, turnip, and corn are taken to be 213 W/m^2 (25 kLx), 469 W/m^2 (55 kLx), and 685 W/m^2 (80 kLx), respectively [27], [28]–[31]. Since the reported values for PAR_{th} for some crop species may vary over a small range, average values are assumed here to illustrate our approach.

Let us now define a yield ratio for the useful daily PAR

$$Y_{\text{PAR}} = \frac{\text{PAR}_{u,\ \text{AV}}}{\text{PAR}_{u,\ \text{open}}}. \quad (4)$$

We note that for any PV configuration, $\text{PAR}_u(\text{AV}) \leq \text{PAR}_u\ (\text{open})$ which implies that $0 \leq Y_{\text{PAR}} \leq 1$. Similarly, PV energy yield ratio is defined as

$$Y_{\text{PV}} = \frac{\text{PV energy/unit farm area in AV configuration}}{\text{PV energy/unit farm area in standard configuration}}. \quad (5)$$

A world map of the Y_{PV} for fixed and sun tracking bifacial arrays based on our modeling approach has previously been reported [21]–[23]. Similar world maps for Y_{PAR} can easily be obtained.

Finally, LPF is calculated as

$$\text{LPF}\ = Y_{\text{PV}}\ + Y_{\text{PAR}}. \quad (6)$$

The individual components of LPF can be optimized to maximize LPF subject to the constraint of maximum allowed loss in PAR and the crop productivity. In general, the AV modules are installed at a reduced spatial density with p/h ratio being 2 or 3 times larger than a standard PV farm and LPF can range between 1 and 2. Incidentally, it is instructive to compare LPF with LER, which is commonly used to evaluate land productivity as [24]

$$\text{LER}\ = Y_{\text{PV}}\ + Y_{\text{crop(AV)}}/Y_{\text{crop(open)}} \quad (7)$$

where $Y_{\text{crop(AV)}}$ and $Y_{\text{crop(open)}}$ are the *measured* or *simulated* crop yields obtained for AV farm and conventional farm under open farm, respectively. For a typical crop behavior, $Y_{\text{crop}} \propto \text{PAR}_u$, for which LPF and LER are expected to be highly correlated. This provides a great opportunity of using LPF for crop-specific optimization of the PV array density, orientation, and the mobile tilt algorithms without the need for measuring the actual crop yields or using sophisticate crop models that need extensive parametrization. LPF-based optimization could then be combined with other important factors, such as the relative economic importance of food versus energy, LCOE, and crop revenue, to assess, design, and predict the techno-economic performance of an AV farm.

It is worth mentioning that similar to many mechanistic crop growth models, which are based on empirical relationships extracted from some measurements, LPF approach also depends on empirical PAR_{th} values that have been collected at some point. LPF can however provide a much simpler way to explore the AV food-energy yield variation across a relatively large design space and geographic locations as compared to the approaches that use more sophisticated crop models.

An important limitation that is common to many of the reported crop models for AV relates to their ability to model the varying shade sensitivity of crops across the day. LPF approach based on PAR_u provides a simple way to address this. For example, during early mornings/late afternoon when the light intensity is usually lower than PAR_{th}, the AV shades can have a strong effect on PAR_u and could impact the crop yield. On the other hand, the incident PAR can well exceed the PAR_{th} for many crops during times closer to the noon for which the AV shading may have a negligible effect on PAR_u and the crop yield. Besides the intradaily shade sensitivity variation, crops may have a significant difference in their shade sensitivity across various development stages. This interstage variation is although not included in our current model, it is relatively straightforward to extend the presented approach to incorporate this effect. A possible way could be to estimate crop yield based on a weighted average of Y_{PAR} that are separately calculated for each of the developmental stages. The weights can be assigned based on crop's relative shade sensitivity during the respective stage that may be known through prior literature or by conducting a field study. Alternatively, PAR_{th} could itself be made variable using a similar approach to reflect the varying interstage light sensitivity for the crop. Future work is planned to explore this effect in more detail.

It should be noted that besides photosynthesis, the light variation in the waveband between 300–800 μm may cause other physiological changes in the plant related to pigment biosynthesis, photoperiodism, phototropism and photomorphogenesis [27]. These effects may also influence the AV crop yield in some cases but are considered beyond the scope of the first order analysis that is based on photosynthesis.

III. Results

The results are obtained for bifacial AV systems with c-Si PV modules of height (h) that are mounted at an elevation (E) above the ground and are separated by row-to-row pitch (p) in either N/S or E/W faced orientations. The albedo reflection (R_A) is taken as 0.25 for simplicity although the practical albedo varies with the type of vegetation and time of the day [33]. As an illustrative example, all the simulations are performed for Lahore, Pakistan unless otherwise specified.

A. Fixed Tilt Agrivoltaic Bifacial Farms

Most of the existing fixed tilt AV farms today rely on N/S faced monofacial panels. With increasing commercial viability of bifacial panels, bifacial AV farms in standard N/S faced fixed tilt, and E/W faced vertical tilt are being increasingly explored. Here, we explore the relative performance of N/S tilted versus E/W vertical bifacial PV configurations. The spatially averaged PAR on the ground as a function of time of the day is shown in Fig. 5 for open farm and under different p/h densities for N/S faced (left column) and E/W faced vertical (right column) PV arrays across various months. For both orientations, PAR reduces with increasing array density, as expected. An important difference in the trends for the two orientations is that for E/W, PAR reduction is more prominent during early morning and closer to sunset, whereas for N/S arrays, PAR reduces more around the middle part of the day. As a result, E/W vertical arrays tend to meet the PAR_{th} around noon but remains lower than the threshold during early morning and late afternoon. The opposite is true for the N/S faced arrays. The implication of this difference in the temporal behavior for crop yield varies with PAR_{th} and p/h.

Fig. 6 shows the monthly Y_{PAR} for the N/S and E/W faced arrays. Y_{PAR} decreases as a function of increasing array density, as expected. The relative decrease in Y_{PAR} as a function of array density is, however, highly dependent on the crop's PAR_{th}. While Y_{PAR} for lettuce remains above 80% for full or lower array densities, turnip and corn show significantly lower Y_{PAR} at full or higher array densities. An important difference between the trends for N/S and E/W faced arrays is a higher seasonal variation of Y_{PAR} for the former, which is more prominent for the shade sensitive crops. A peak centered around the month of May is observed for turnip and corn, which gradually lowers as we move towards winter months. The seasonal variation is less prominent for lower array density ($p/h > 2$). The seasonal variation of crop-specific Y_{PAR} should be considered to assess the crop yield while comparing various PV array topologies. It is worth noting that, for lettuce, the same amount of light is used more efficiently in N/S faced system as

there is less excessive sunlight above PAR_{th} as compared to that in E/W faced system [see Fig. 6(a) and (d)]. For corn, the E/W faced system provides a better PAR_u since there is a minimal excessive sunlight above PAR_{th} across the day. This

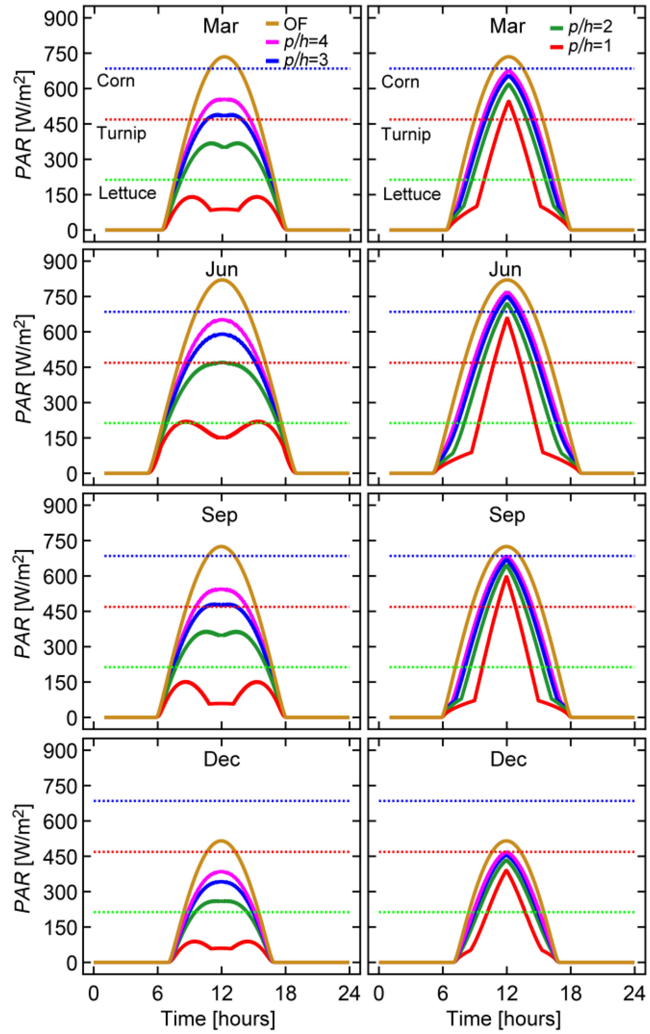


Fig. 5. PAR available to crops under open farm and varying fixed tilt PV array density from half to double for (a) N/S faced arrays (left column) and (b) E/W faced vertical arrays (right column) for various months. Horizontal lines represent the PAR_{th} for lettuce, turnip, and corn.

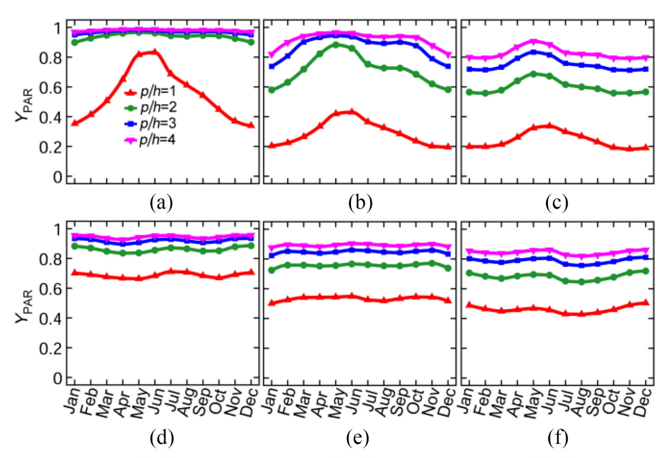


Fig. 6. Monthly Y_{PAR} for three different crops under N/S (top row) and vertical E/W (bottom row) faced fixed tilt PV farms at different PV array densities.

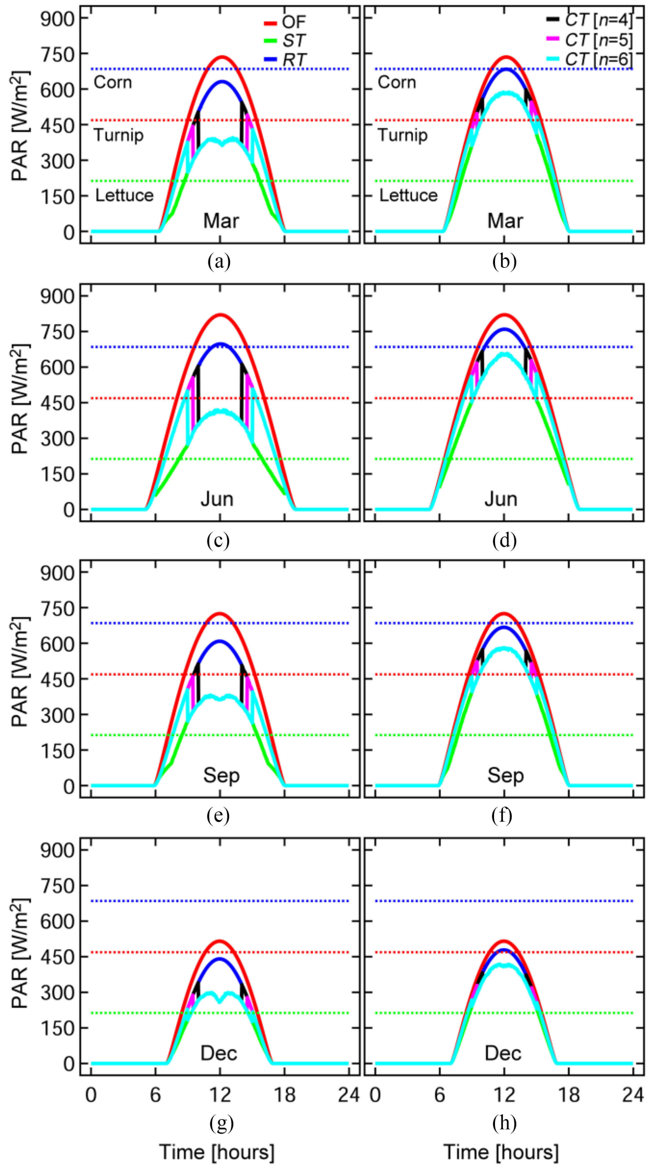


Fig. 7. PAR available to crops under open farm and single axis tracking PV arrays at (a) full density (left column) and (b) half density (right column) for various months. Horizontal lines represent the PAR_{th} for lettuce, turnip, and corn.

effect is more prominent for higher density arrays [see Fig. 6(c) and (f)].

B. Tracking Agrivoltaic Bifacial Farms

It should be Fig. 7 show the spatially averaged daily PAR variations under open farm and for different single axis tracking schemes at $p/h = 2$ and $p/h = 4$, respectively, for the months of March, June, September, and December. The relative PAR difference between ST and RT is smaller towards early morning and late afternoon but grows larger around noon. For CT, the tracking scheme switches from RT to ST for a few hours around noon. The customization of this switching for a given crop allows a great flexibility to maximize the PAR_{th} requirement for a given month. Although PAR reaching to the ground decreases when switching from RT to ST, values close to PAR_{th}could still be achievable due to high sunlight intensity closer to noon. For full array density, a noticeable difference in PAR between RT and ST is also observed in early morning and late afternoon. For half density, the overall difference in PAR between the various tracking is relatively small as compared to that for the full density. Moreover, during the early morning and late afternoon, difference in PAR between the tracking schemes is negligible for the half density.

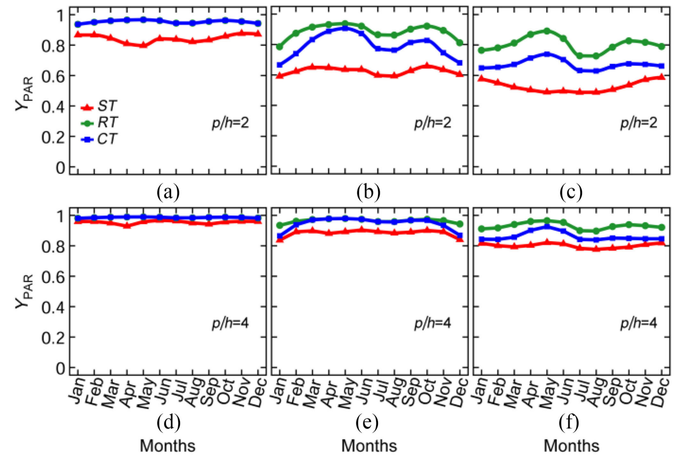


Fig. 8. Monthly Y_{PAR} for three different crops under ST, RT, and CT single axis tracking schemes at full (top row) and half (bottom row) density PV arrays.

Fig. 8 shows Y_{PAR} for ST, RT, and CT ($n = 2$) schemes at $p/h = 2$ and $p/h = 4$ for the three crops across all months. It can be noted that ST results in limiting Y_{PAR} below 60% for the full density array except for lettuce. Using RT, Y_{PAR} recovers to $\geq 80\%$ for all crops except for a few summer months where corn shows a slightly lower Y_{PAR}. For half density arrays, ST provides $Y_{\mathrm{PAR}} \geq 80\%$ for all three crops across all months. The customization of CT can optimize Y_{PAR} within the margins available between RT and ST, which widens for the full density as compared to the half density.

Fig. 9 compares the annual Y_{PV}, Y_{PAR}, and LPF for all fixed and mobile PV schemes under study at full and half densities of the PV arrays. The lowest and highest Y_{PV} is for the RT and ST tracking schemes while the opposite is true for Y_{PAR}. The trend for LPF is closer to that of Y_{PV}. It should be noted that the relative difference between Y_{PV}, Y_{PAR}, and LPF for E/W versus N/S faced fixed tilt panels is not significant at half density. The maximum LPF is about 1.6 and 1.9 for half and full density arrays, respectively.

C. Model Comparison With Experimental Data

Model to experiment comparison is done using a recently published field data [25] from an AV farm at Heggelbach, Germany having AV installation covering one third of the total area of 2.4 hectares with the installed capacity of 194.4 KW_p [34]. Crop yields from the field data for winter wheat and potato are compared with Y_{PAR} from the model for the same crops and the field location in Fig. 10. PAR_{th} of 1000 $\mu mol\ /m^2 - s$ and

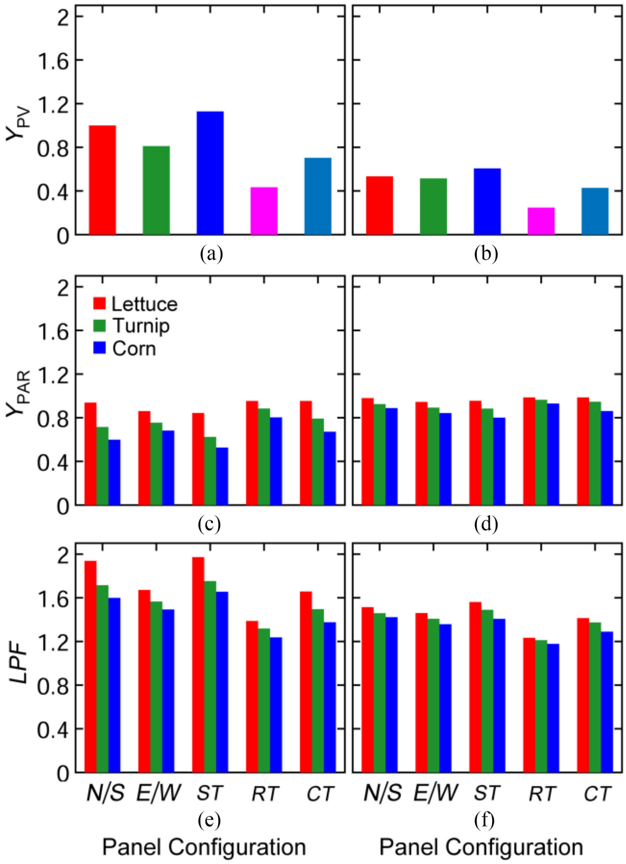


Fig. 9. (a) PV energy yield ($Y_{\rm PV}$), (b) useful PAR yield ($Y_{\rm PAR}$), and (c) LPF for various fixed tilt and mobile panel configurations. The left and right columns show results for full density ($p/h = 2$) and half density ($p/h = 4$), respectively.

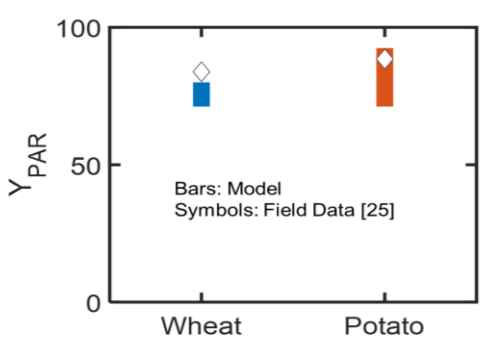


Fig. 10. Comparison of $Y_{\rm PAR}$ with relative crop yield from an AV field study [25].

504 $\mu mol\ /m^2 - s$ for winter wheat and potato, respectively [26], [27] and the typical meteorological data [19] for the field location are used in the model. The relative crop yield in the experiment is determined by taking the ratio of crop yields for AV to that under open farm. The panel density, azimuth, and tilt angles are $p/h = 2.8, 52°$ from south, and $20°$, respectively, for both model and the experiment. The range of the modeled $Y_{\rm PAR}$ in Fig. 10 represents monthly variation, which shows an increase from winter to summer months (as seen in Fig. 5). For potato, the experimental crop yield lies within the range of the modeled $Y_{\rm PAR}$. For winter wheat, the relative crop yield slightly exceeds

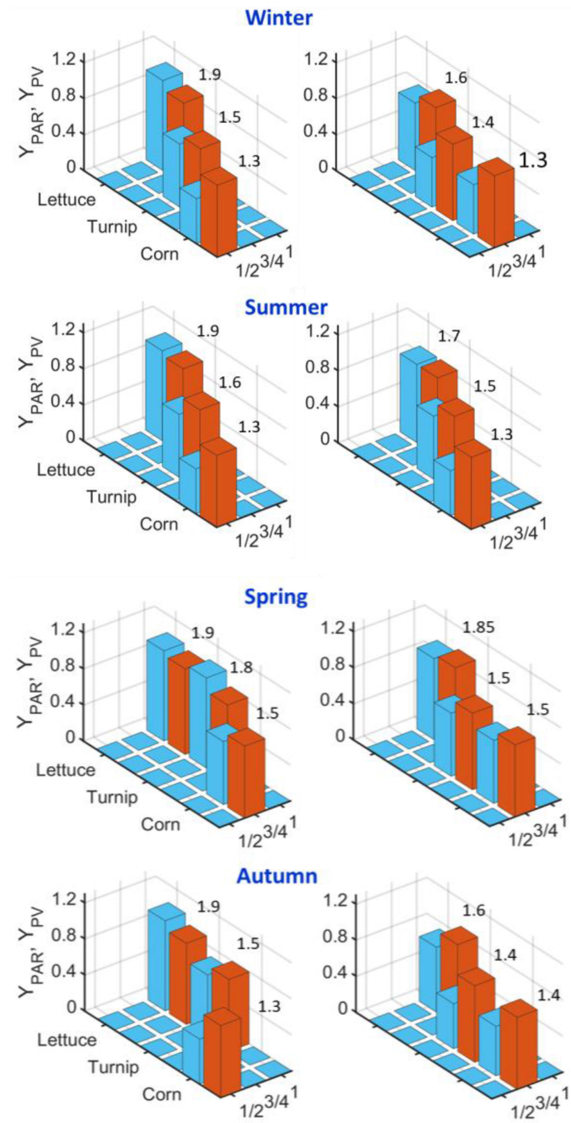


Fig. 11. $Y_{\rm PAR}$, $Y_{\rm PV}$, and LPF for the N/S (left column) and E/W (right column) fixed tilt PV schemes for lettuce, turnip, and corn across various seasons. Only those crop/PV scheme combinations are shown which satisfy the constraint of minimum $Y_{\rm PAR}$ of ~80%. The red and blue colors are for $Y_{\rm PV}$ and $Y_{\rm PAR}$, respectively. The values written on top of each set of $Y_{\rm PV}$ and $Y_{\rm PAR}$ bars are the LPF of the corresponding crop/PV scheme combination.

the modeled $Y_{\rm PAR}$, which may indicate a relatively enhanced radiation use efficiency for the field crop under AV shades.

D. AV Farm Design Under $\boldsymbol{Y}_{\rm PAR}$ Constraint

While LPF can be maximized by increasing the array density, the resulting $Y_{\rm PAR}$ may not always be acceptable from the crop yield perspective. One way to explore the design options and the relative system performance is to specify a constraint on the minimum acceptable $Y_{\rm PAR}$. Fig. 11 shows $Y_{\rm PAR}$, $Y_{\rm YPV}$, and LPF for N/S (left column) and E/W (right column) fixed tilt schemes for the array densities (full, half, or 3/4), which can maximize LPF while satisfying the constraint of minimum $Y_{\rm PAR}$ of $\sim$80% for the crop across all seasons. For the shade tolerant crop (lettuce), LPF $\approx$ 1.9 can be achieved for both PV

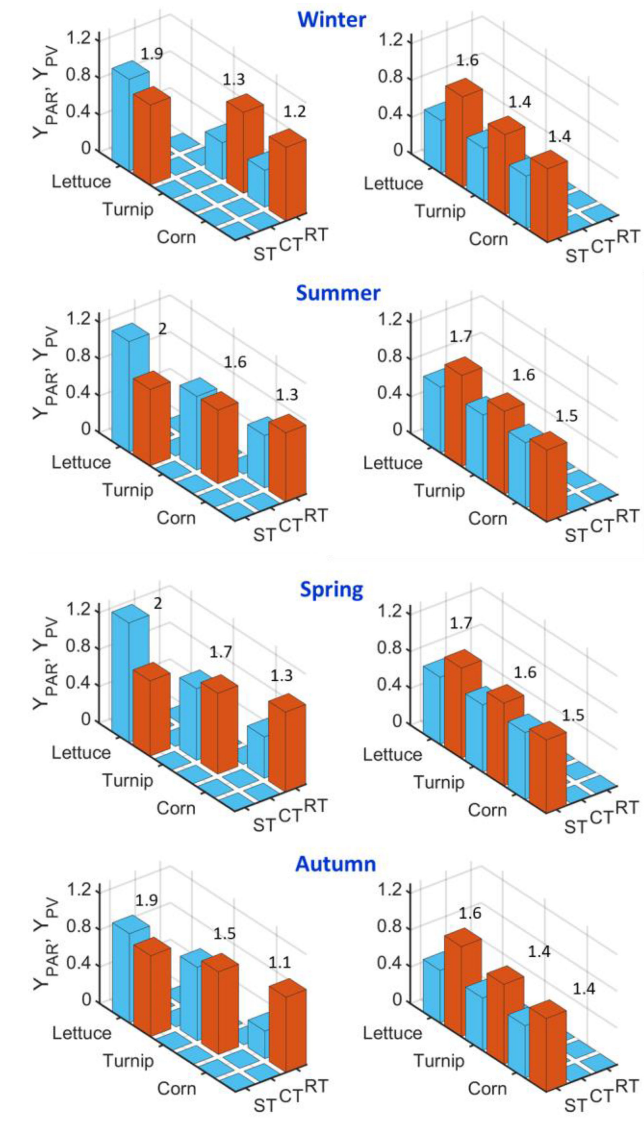


Fig. 12. Y_{PAR}, Y_{PV}, and LPF for single axis tracking schemes (ST, CT, and RT) at half (left column) and full (right column) array density for lettuce, turnip, and corn across various seasons. Only those crop/PV scheme combinations are shown which satisfy the constraint of minimum Y_{PAR} of $\sim$80%. The red and blue colors are for Y_{PV} and Y_{PAR}, respectively. The values written on top of each set of Y_{PV} and Y_{PAR} bars are the LPF of the corresponding crop/PV scheme combination.

orientations at full array density. For moderate shade tolerance (turnip), N/S faced array can provide LPF of 1.5–1.9 with 3/4 array density for winter and full array density for spring, respectively. The E/W vertical array provides LPF of 1.4–1.5 for the corresponding seasons at 3/4 density. For the case of highly shade sensitive crop (corn), both N/S and E/W arrays provide LPF of $\sim$1.3 across all seasons at half and 3/4 array density, respectively.

Fig. 12 shows Y_{PAR}, Y_{YPV}, and LPF for single axis tracking schemes (ST, CT, and RT) at half (left column) and full (right column) array density where the LPF is maximized under the constraint of minimum Y_{PAR} of $\sim$80% for the crop across various seasons. For the shade tolerant crop (lettuce), ST can be implemented for both half and full array densities resulting in LPF of 1.8–2 and 1.5–1.9, respectively. For the case of highly shade sensitive crop (corn), ST can still be implemented for half density arrays, but the full density array requires RT. It can be noted that for the most shade sensitive crop, ST at half array density results in better LPF as compared to RT at full density. Finally, the CT provides an opportunity to maintain the required Y_{PAR} for turnip at full array density when ST fails due to its lower Y_{PAR}.

IV. Conclusion

In this article, we have proposed a simple metric to characterize the efficacy of sunlight sharing between PV modules and the crops for AV systems. The approach is based on evaluating the AV energy yield and the daily PAR utilized in crops' photosynthesis, relative to the standalone PV and open crops, respectively. LPF is introduced as a metric to indicate the overall efficacy of sunlight sharing between the crops and the PV modules. The LPF varies with the crop's sensitivity to the shade and the system parameters such as the spatial density of PV arrays, panel tilt/orientation, and the tracking scheme. We have explored these design parameters taking lettuce, turnip, and corn as representative crops for low, moderate, and high shade sensitivity, respectively. It is shown that although high density arrays and standard sun tracking can maximize LPF, the PAR requirement for the crop can be drastically reduced. To ensure an acceptable crop yield while optimizing LPF, a minimum constraint on the useful daily PAR reduction for the crop should be enforced. We provide an illustrative example of exploring the system design under a constraint of at least $\sim$80% useful daily PAR for the crops relative to an open farm and present the following key points.

1) Crops that are highly shade tolerant allow LPF of $\sim$2, while the crops having moderate and high shade sensitivity permit LPF in the range of 1.2 to 1.8, respectively, across various seasons.
2) Full array density may be used for shade tolerant crop across all seasons, whereas half or 3/4 array density is required for moderate to highly shade sensitive crops, respectively, for various seasons. These results are consistent with empirical results reported in the field experiments [4], [25].
3) For the fixed tilt PV arrays that include N/S faced optimally tilted and E/W faced vertical bifacial configurations, the relative difference in the performance is negligible for the half density arrays but becomes significant at full array density for which N/S faced arrays show better LPF.
4) E/W faced vertical PV stands out with a least variation in the seasonal crop performance and may be the preferrable fixed tilt scheme since it can provide other important benefits such as low elevation mounting, easy movement of farm equipment, and reduced soiling loss.
5) For full PV array density, the standard PV tracking can provide LPF $\sim$2 for the shade tolerant crops but customized or reverse tracking schemes are required for moderate and shade sensitive crops providing LPF 1.2–1.6 depending on the season. Reducing the PV array density to half allows

implementing the standard solar tracking with the LPF of ∼1.4–1.7 for both shade sensitive and tolerant crops, respectively, across all seasons.

6) For the most shade sensitive crop, ST at half array density provides better LPF (∼1.5) as compared to RT at full density, which permits LPF ∼1.2.

The approach and performance metrics presented in this article to characterize AV systems can be valuable for an initial technology assessment and design optimization, comparative analysis of AV system configurations, and an early indication of the crop-energy yields. In particular, this article highlights that LPF formulism offers an improved design of experiments. When combined with field study, our approach provides an opportunity to develop deeper insights into the farm productivity by evaluating relative difference between LPF and LER. Although the LPF approach is applied to single crops, its multicropping generalization is easy to develop. Finally, we would like to emphasize that the region-specific complexity of policy for food and energy is important in determining the optimal farm design. For example, the relative socio-economic significance of food versus energy and relative LCOE for AV versus standard PV farms are important considerations. In principle, the price-performance ratio for AV could be better because of the agricultural production serving as the second resource of revenue in addition to the electricity. The future work on this topic should quantify these region-specific practical considerations for the techno-economic design and assessment of AV technologies.

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