Optimization of PV Array Density for Fixed Tilt Bifacial Solar Panels for Efficient Agrivoltaic Systems

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***Abstract*—Agrivoltaic systems are innovative production systems for dual production of solar energy and agriculture from the same land. The technology has a great potential to holistically address food-energy-water challenges across globe. The design of solar PV arrays for agrivoltaics differs from a standard solar system due to the constraints of shading at the crop level. We explore optimization of PV array row density for fixed tilt bifacial PV for a given crop and the food-energy productivity requirements from the system. Bifacial PV arrays in vertical tilt facing East/West are compared to North/South faced bifacial PV arrays at fixed optimal tilt and relative productivity of energy and food at a given array density is investigated using daily temporal calculations of sunlight at PV and crop levels. We further explore the effect of tilt angle for fixed tilt agrivoltaic systems and explore its effect on energy and drop shadows on crops for the two PV orientations.**

***Index Terms*—Agrivoltaic (AV), Bifacial, East/West (E/W), Global Ground Irradiance (GGR), North/South (N/S).**

I. Introduction

As the world population is estimated to approach 10 billion people by mid-century, providing all the needs of mankind from the limited area of Earth's land would be an important challenge of sustainability [1]. Energy and food are two of the indisputable and principal requirements for human development. The growing energy demand and increasing population require optimization between food and energy nexus. Agrivoltaic (AV) systems are one of the most emerging fields for the optimization of the food and energy in a given specified area of land. A number of studies showed that with the help of AV systems, the productivity of land can be increased with additional benefits of crop yield improvement, irrigation budget reduction and preservation of agriculture land [2]. In these system, solar panels are installed in such a way to cover the partial crops with optimal density, tilt, and elevation, which is a trade-off between crop and energy production. The photovoltaic (PV) land covering technique also protects the crop production from harmful weather conditions and it also reduces the water evaporation in the farm by which the water budget reduced by 20% [3] and providing more desirable conditions for crop yield as compared to full light.

Although the concept of collocating the agriculture and PV was initially floated in 1982 by Goetzerberger [4], the first prototype of AV system was installed by Duprez *et al.,* [5], [6] in France in 2010, where PV modules were installed at an elevation of 4 meters above ground. By introducing the concept of Land equivalent ratio (*LER*), it was shown that land productivity can be increased by ∼35–73% when solar panels were arranged at half and full densities that correspond to pitch (row-to-row spacing) being twice and four times the height of the panels, respectively. This showed promising potential of these AV systems and further recent studies also confirmed the benefits of AV systems [7].

Although a lot of studies have been carried out, yet the potential of East/West and North/South mounted bifacial solar modules in AV systems have not been explored yet. Further, the crop-specific PV configurations in AV systems needs to be properly explored. The purpose of this paper is to compare the potential benefits of East/West (E/W) and North/South (N/S) mounted bifacial PV modules for different seasonal crops. In particular, we explore the effect of panel density, elevation and tilt angle on energy yield as well as on the crop growth.

This paper is divided into four sections. In Section II, we describe the modeling approach. Results are discussed in Section III, whereas Conclusions are furnished in Section IV.

II. Modeling Approach

A. Properties of Solar Farm:

The solar farm consists of bifacial solar modules of height (h), mounted at an elevation (E) above the ground and separated by row-to-row pitch (p) is shown in Fig. 1. The modules are oriented either in N/S or E/W configuration and tilted at an angle (β), which is kept at 90° and 40° for E/W and N/S

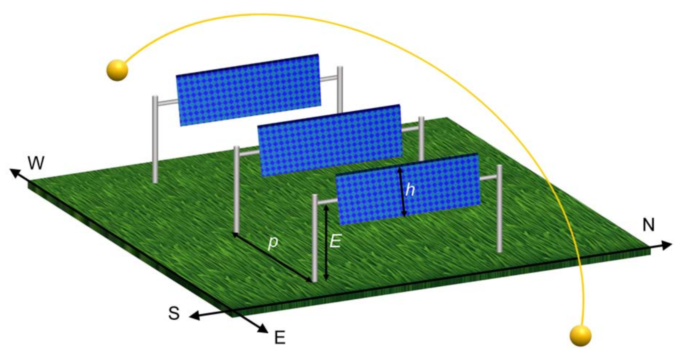

Fig. 1. The schematic diagram of East/West (E/W) oriented vertical bifacial PV farm.

TABLE I
EQUATIONS USED TO COMPUTE ENERGY AT PANEL AND CROP LEVELS. [2]

$I_{\text{global}} = I_{\text{dir}} \times \cos(\theta_z) + I_{\text{diff}}$	$I_{\text{diff}} = DF \times I_{\text{global}}$; $I_{\text{dir}} = \frac{I_{\text{global}} - I_{\text{diff}}}{\cos(\theta_z)}$	$I_{\text{M,dir}}(z) = [1 - R(\theta_{\text{AOI}})]\, \eta_{\text{dir}} \times I_{\text{dir}} \times \cos(\theta_{\text{AOI}})$
$\psi_{\text{sky}}(z) = \tan^{-1}\left[\frac{h - z \cdot \sin\beta}{p - (h-z)\cos\beta}\right]$	$F_{\text{dz}\to\text{sky}}(z) = \frac{1}{2}\left[1 - \sin\left\{\psi_{\text{sky}}(z)\right\}\right]$	$I_{\text{M,diff}}(z) = \eta_{\text{diff}}\left(I_{\text{diff}} \times F_{\text{dz}\to\text{sky}}\right)$
$I_{\text{gnd;dir}} = I_{\text{dir}} \times \cos(\theta_z)$	$I_{\text{M,Alb:dir}}(z) = I_{\text{gnd;dir}} \times \eta_{\text{diff}} \times R_{\text{A}} \times F_{\text{dz}\to\text{Ugnd}}(z)$	$\psi_{\text{gnd}}(z) = 90 - \beta - \tan^{-1}\left[\frac{z \cdot \sin\beta}{p + z \cdot \cos\beta}\right]$
$F_{\text{dz}\to\text{gnd}}(z) = \frac{1}{2}\left[1 - \psi_{\text{gnd}}(z)\right]$	$I_{\text{M,Alb:diff}}(z) = \eta_{\text{diff}} \times I_{\text{diff}} \times R_{\text{A}} \times F_{\text{dz}\to\text{gnd}}(z)$	$G_{\text{GR}} = I_{\text{gnd;dir}} + I_{\text{diff}}$

orientation respectively throughout the paper, unless otherwise specified. It is important to note that 40° is optimal tilt angle for bifacial N/S facing modules for Lahore, Pakistan [2] whereas vertically installed solar modules are inherently more resilient to soiling (dust accumulation) losses as compared to tilted solar modules [8]

B. Calculation of Energy and Crop Light

The sun's global horizontal irradiance (I_{global}) is composed of direct (I_{dir}) and diffuse (I_{diff}) components. Therefore, for energy (I_{PV}) calculation, we first decompose global I_{global} into I_{dir} and I_{diff} using the same approach as reported in [2], [9] [10]. For irradiance collection on module from (I_{dir}), angle of incident (θ_{AOI}) between the sun and the normal of the module surface is computed. Further, the energy harvested from (I_{diff}) or albedo, we use the same view factor approach as reported in [2]. Along with contributing in energy yield, a part of I_{diff} and I_{dir} also reaches the ground and termed as the global ground radiation (G_{GR}). G_{GR} is the light responsible for albedo collection on the modules as well as crop growth. The equations used for modeling of all the parameters are summarized in Table I.

III. RESULTS AND DISCUSSION

A. Effect of Pitch

Fig. 2(a) and 2(b) show I_{PV} produced per pitch by N/S and E/W mounted bifacial solar farm for different module densities, whereas the corresponding G_{GR} is plotted in Fig. 2(c) and 2(d) respectively. I_{PV} increases with decrease in module density, due to larger number of modules per pitch, whereas G_{GR} reduces with increasing module density due to more surface coverage by dense PV modules, and their high shading effects. The maximum G_{GR} is achieved for June irrespective of module configuration. On the other hand, I_{PV} is maximum for June in E/W configuration due to high I_{global}. For N/S configuration, I_{PV} is maximum for September due to clearer sky and optimal β (40°) for N/S configuration for September.

Fig. 3(a) and 3(b) show the change in I_{PV} by varying module density with respect to conventional half PV module density (*i.e.* $p/h = 2$) for N/S and E/W PV configurations respectively. The effect of module density for N/S configuration is

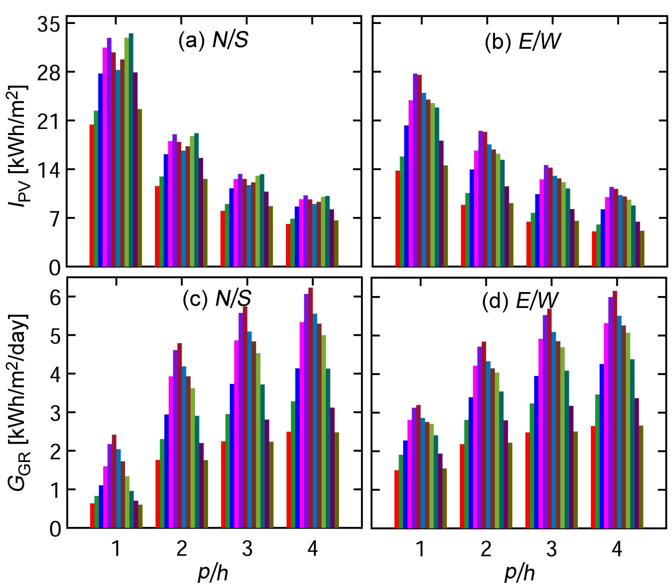

Fig. 2. Energy (I_{PV}) produced by PV modules and the global ground irradiance (G_{GR}) available for crops for different months for both N/S and E/W mounted modules for various module densities.

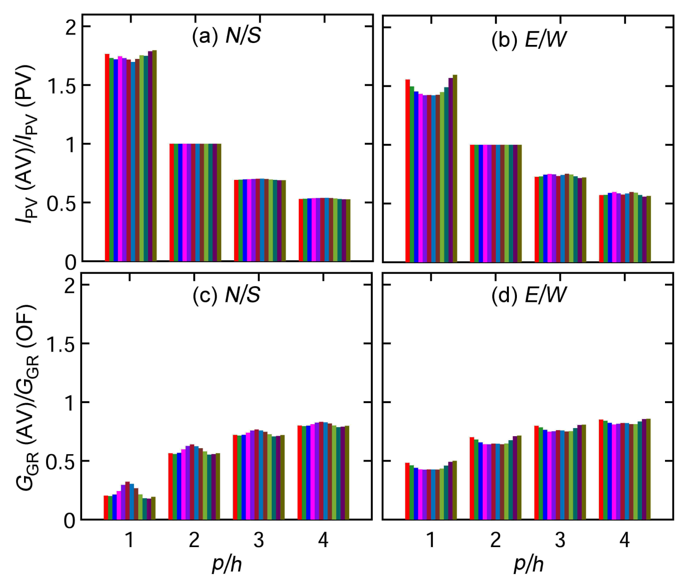

Fig. 3. (a,b) Change in I_{PV} in AV systems with respect to conventional PV farms [$p/h = 2$], and (c,d) Change in G_{GR} in AV systems with respect to open agricultural farm (OF) for various module densities.

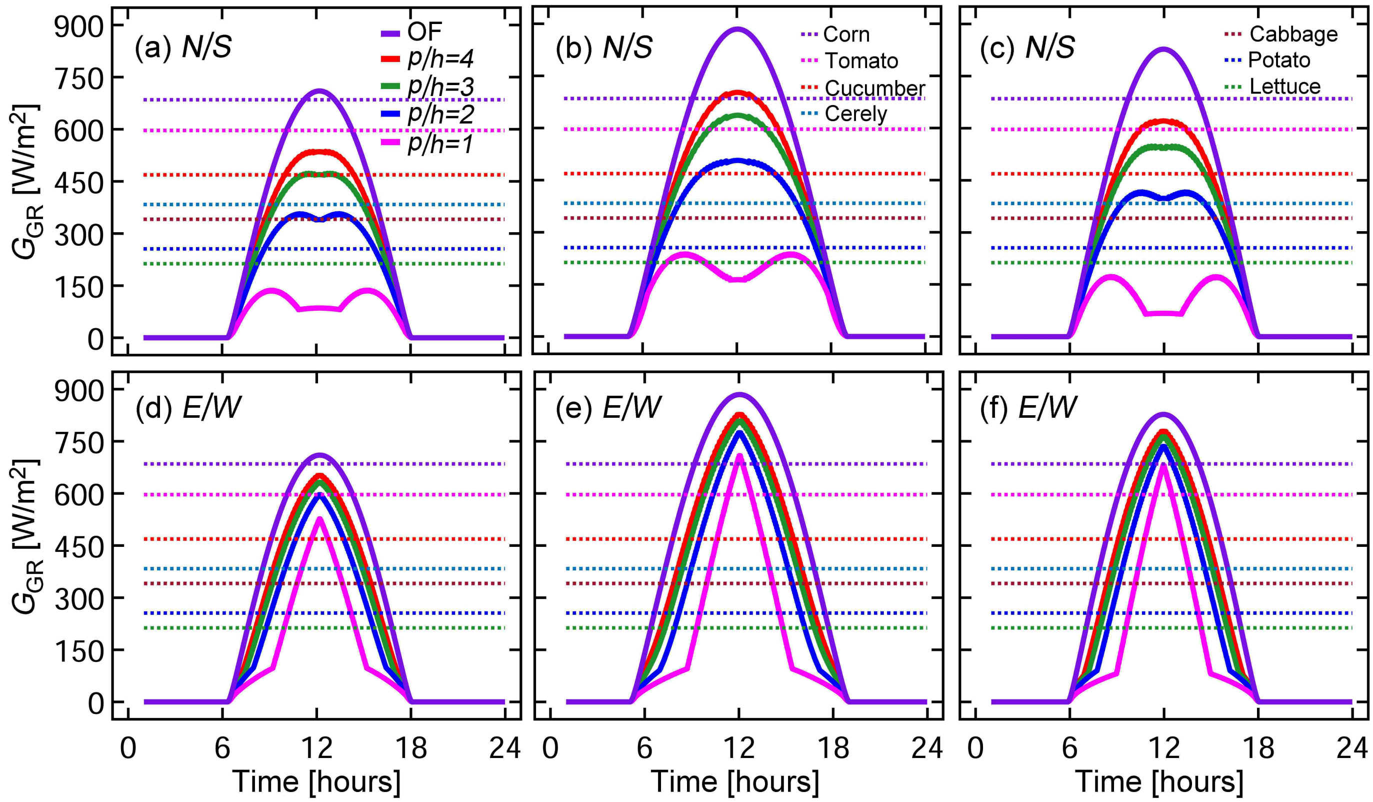

Fig. 4. Variation in G_{GR} over the day for N/S and E/W mounted PV modules for (a,d) March, (b,e) June, and (c,f) September for various module densities. Dotted lines represent G_{GR} required by different crops at LSP.

TABLE II
G_{GR} OF PAR REQUIRED FOR DIFFERENT CROPS AT LSP [11]

Crop Name	G_{GR} at LSP [kLx]	G_{GR} at LSP [W/m^2]
Corn	80	684.9
Tomato	70	596.6
Cucumber	55	468.8
Cerely	45	383.5
Cabbage	40	340.9
Potato	30	255.7
Lettuce	25	213.1

significant as compared to that for E/W configuration for all months, with 3 times decrease in I_{PV} for N/S case, which is almost 2.5 times for E/W case when p/h is increased 4 times. Similarly, Fig. 3(c) and 3(d) show the change in G_{GR} by varying module density with respect to open agricultural form (OF) for N/S and E/W PV configurations respectively. Similar to I_{PV}, effect of module density on G_{GR} is greater for N/S configuration as compared to that for E/W configuration.

As listed in Table II, a certain amount of G_{GR} during a day is required for each crop to maintain its full yield. The maximum G_{GR} is termed as light saturation point (LSP), with units in Lx, which is the photon flux of Photosynthetically Active Radiation (PAR), which ranges from 400–700 nm [11]. In order to explore which module density best satisfies daily G_{GR} requirements of different crops, G_{GR} as a function of time is plotted in Fig. 4 for N/S and E/W configurations for different months. The dotted lines in Fig. 4 represent G_{GR} required at LSP for different crops. For E/W case, $p/h = 4$ best satisfies the G_{GR} requirements for all months and for all crops with slight compromise on crop growth except corn crop in March. But on the other hand, for N/S case, the best module density highly depends upon season and crop. For example, $p/h = 4$ best suites for most of the crops for September, but in June, it is not suitable for crops having low G_{GR} requirements. Fig. 4 provides an insight how crop-specific p/h could be achieved for different crop seasons.

B. Effect of Tilt Angle

Fig. 5(a) shows the effect of β on I_{PV} of mono/bifacial PV modules for N/S and E/W configurations. N/S mounted bifacial module performs best for β ranges from 0–75°. For $\beta > 75°$, E/W mounted bifacial module performs optimally. Similarly, N/S mounted monofacial module performs better for every β as compared to its E/W counterpart. The Fig. 5(b) shows the effect of β on G_{GR} for N/S and E/W configuration. The trend is simply invert as the case of I_{PV}, with higher G_{GR} for E/W case up to $\beta = 75°$, and then decreases for $\beta > 75°$.

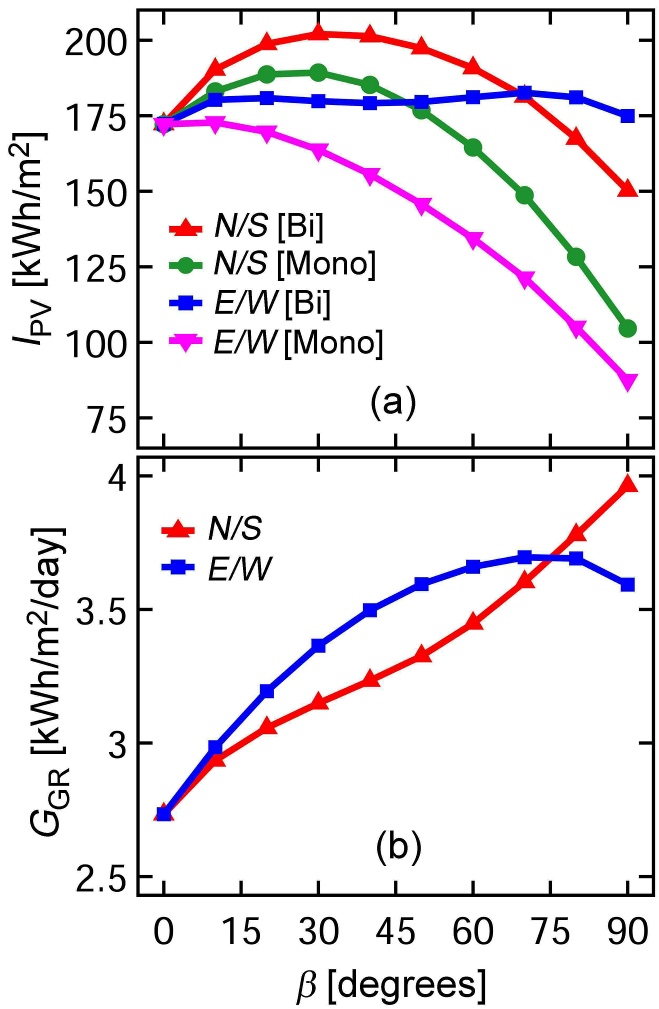

Fig. 5. Effect of β on I_{PV} and G_{GR} for E/W and N/S mounted modules.

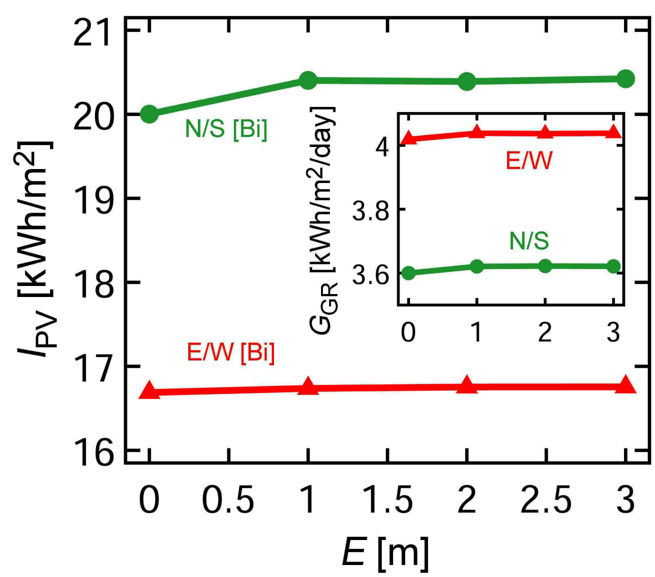

Fig. 6. Effect of E on I_{PV} and G_{GR} for E/W and N/S mounted modules.

C. Effect of Elevation

The effect of E on I_{PV} is shown in Fig. 6 for N/S and E/W configurations. I_{PV} slightly increases by increasing elevation up to 1 meter and then becomes constant for both cases. This is due to increased albedo collection with increasing E. The inset of Fig. 6 shows the effect of E on G_{GR} which almost remains constant with E for both N/S and E/W cases. The Fig. depicts that a higher amount of I_{PV} can be achieved if modules are installed at certain E, with no effect on the crop available G_{GR}.

IV. Conclusions

We have modeled the PV energy output and temporal shading behaviors at crop levels for agrivoltaic systems that are based on fixed tilt bifacial solar PV arrays. The PV array density is varied to find an optimal value based on the daily sunlight needs of the given crop. Results for two different panel orientations (*i.e.*, East/West vs. North/South faced) are compared based on the sunlight availability for crops and PV energy output. The temporal behavior of spatially integrated Photosynthetically active radiation (PAR) density available to crops throughout the day significantly vary with PV orientation and therefore the optimal array density is orientation dependent.

References

[1] U. D. of Economic and P. D. Social Affairs, "World population prospects: The 2017 revision. key findings and advance tables. working paper no. esa/p/wp/248," 2017.

[2] R. Younas *et al.*, "Agrivoltaic farm design: Vertical bifacial vs. tilted monofacial photovoltaic panels," *arXiv preprint arXiv:1910.01076*, 2019.

[3] Y. Elamri *et al.*, "Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces," *Agricultural water management*, vol. 208, pp. 440–453, 2018.

[4] A. Goetzberger and A. Zastrow, "On the coexistence of solar-energy conversion and plant cultivation," *International Journal of Solar Energy*, vol. 1, no. 1, pp. 55–69, 1982.

[5] C. Dupraz, *et al.*, "Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes," *Renewable energy*, vol. 36, no. 10, pp. 2725–2732, 2011.

[6] C. Dupraz *et al.*, "To mix or not to mix: evidences for the unexpected high productivity of new complex agrivoltaic and agroforestry systems," in *Proceedings of the 5th world congress of conservation agriculture: Resilient food systems for a changing world*, 2011.

[7] R. Mead *et al.*, "The concept of a 'land equivalent ratio'and advantages in yields from intercropping," *Experimental Agriculture*, vol. 16, no. 3, pp. 217–228, 1980.

[8] A. Ullah, H. Imran, Z. Maqsood, and N. Z. Butt, "Investigation of optimal tilt angles and effects of soiling on pv energy production in pakistan," *Renewable energy*, vol. 139, pp. 830–843, 2019.

[9] M. R. Khan *et al.*, "Vertical bifacial solar farms: Physics, design, and global optimization," *Applied energy*, vol. 206, pp. 240–248, 2017.

[10] H. Imran, M. H. Riaz, and N. Z. Butt, "Optimization of single-axis tracking of photovoltaic modules for agrivoltaic systems," in *IEEE 47th Photovoltaic Specialists Conference (PVSC)*, 2020.

[11] S. Tazawa, "Effects of various radiant sources on plant growth (part 1)," *Japan Agricultural Research Quarterly*, vol. 33, pp. 163–176, 1999.