Optimization of Single-Axis Tracking of Photovoltaic Modules for Agrivoltaic Systems

Hassan Imran
Department of Electrical Engineering
School of Science and Engineering
LUMS, Lahore, 54792, Pakistan
Email: hassan.imran.ee@gmail.com

Muhammad Hussnain Riaz
Department of Electrical Engineering
School of Science and Engineering
LUMS, Lahore, 54792, Pakistan
Email: hussnainriaz8@gmail.com

Nauman Zafar Butt
Department of Electrical Engineering
School of Science and Engineering
LUMS, Lahore, 54792, Pakistan
Email: nauman.butt@lums.edu.pk

***Abstract*—Agrivoltaics is an emerging technology of collocating solar photovoltaics with agriculture that has many potential synergetic food-energy-water benefits. The design of agrivoltaic systems demands a careful balance for sharing sunlight between solar panels and crops to ensure an optimal food-energy productivity. We explore the optimal single-axis tracking schemes for agrivoltaics that can provide the precise balance of sunlight between PV and crops. The single-axis tracking schemes are applied to bifacial panel arrays in two different PV orientations, *i.e.,* East/West vs. North/South faced. By modeling the temporal variations of drop shadows on crops and the known requirements of photosynthetically active radiation (PAR) by the crop, we propose customized solar tracking schemes that vary between standard sun tracking and reverse sun tracking during the day according to the crop requirement. During the early daytime after sunrise and closer to the sunset, PAR is lower than the saturated PAR for the plants. Closer to noon, available PAR can exceed the crop needs. An optimal algorithm ensures that the PAR available to the crops remains closer to its required PAR so that the excess sunlight could be harvested by the PV arrays. The seasonal variation in customized tracking schemes is explored for the two PV orientations.**

***Index Terms*—Agrivoltaics, bifacial, Photovoltaics, single-axis tracking.**

I. Introduction

The demands for food, energy and water (FEW) are approaching unprecedented levels as the global population is estimated to approach 10 billion people by 2050 [1]. Addressing the environmental concerns along with fulfilling the FEW demands are the indisputable challenges the humanity will have to face in coming decades. This requires clean and renewable energy resources that could solve the FEW demands with least environmental footprints. Among all renewable energy resources, solar energy is best source of green and sustainable energy with the advantage of limited environmental impacts [2]. Large scale Photovoltaic (PV) farms require a huge area of land, which results in their direct competition with global surface area, such as land for agriculture versus PV farms. Agrivoltaic (AV) systems, consisting of PV modules a few meters above crop land, recently emerged as an opportunity to resolve the competition for land use between energy and crop production [3].

A number of studies have demonstrated promising potential of AV systems in terms of land productivity, but these studies were either limited to shadow-tolerant crops or sacrificed crop yield [3]–[5]. For example, 18-19% loss was found in yield of crops such as wheat and potatoes grown underneath the south-facing elevated bifacial solar modules [6]. Since maintaining yield of major crops such as wheat, rice, potatoes *etc.* is of highest priority, Valle *et al.,* [7] explored customized single-axis tracking (*CT*) schemes for lettuce where modules were placed normal to sunrays only for a specific duration depending upon the amount of light needed to maintain efficient crop growth. Although *CT* schemes showed promising potential in terms of crop yield, yet they are still lower than conventional tracking (*ST*) in terms of land productivity. Therefore, it is upfront that the crop-specific optimization of these schemes could result in efficient crop growth as well as better land productivity. The purpose of this study is to investigate different solar tracking schemes for bifacial East/West (E/W) and North/South (N/S) mounted solar modules and their potential benefits for seasonal crop growth. In particular, we answer the following key questions: (i) How the performance of AV farms is varied for E/W and N/S facing bifacial farms for different tracking schemes, (ii) How the module tilt angle is changed for E/W and N/S oriented modules for different seasons, and (iii) How the module density affects crop growth.

This paper is divided into four sections. Section II describes the modeling approach. Section III discusses the results and the conclusions are provided in Section IV.

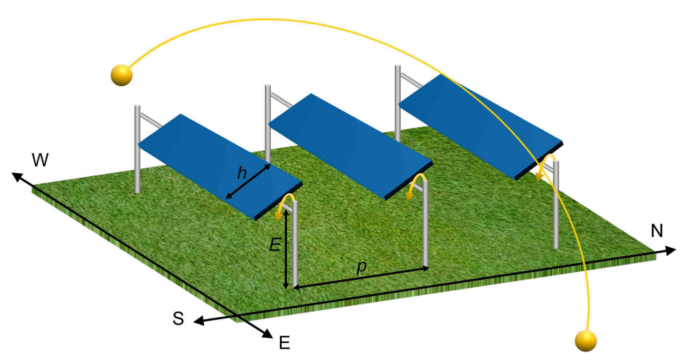

Fig. 1. The schematic diagram of North/South (N/S) oriented mobile bifacial PV farm.

TABLE I
EQUATIONS USED TO COMPUTE ENERGY AND CROP LIGHT [8]

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

II. MODELING APPROACH

A. Tracking Schemes

The solar farm consists of bifacial solar modules of height (h) that are mounted at an elevation (E) above the ground, and separated by row-to-row pitch (p) is shown in Fig. 1. The modules are mounted either in N/S or E/W orientation and are made mobile through single-axis tracker. The tracking scheme when module faces normal to sunrays is termed as solar tracking (*ST*) whereas the scheme when module face is parallel to sunrays is termed as reverse tracking (*RT*). Moreover, three different customized tracking (*CT*) schemes are explored when *ST* is implemented during n number of hours, with $n/2$ number of hours on either side of the midday, unless otherwise *RT* is implemented for rest of the day. For the performance comparison, these schemes are compared with fixed-tilt bifacial farms, the tilt angle for N/S and E/W configurations is kept at 40° and 90° respectively. It is important to note that 40° is optimal tilt angle for bifacial N/S facing modules for Lahore, Pakistan [8] whereas vertically installed solar modules are inherently more resilient to soiling (dust accumulation) losses as compared to tilted solar modules [9].

B. Calculation of Tilt Angle

To compute the time dependent tilt angle (β) of module, first we compute angle of incident (θ_{AOI}) between the sun and the normal of the module for the desired tracking scheme. As θ_{AOI} is the angle between the sun and the normal of the module surface [8], therefore it is 0° for *ST* and 90° for *RT*. Fig. 2 shows θ_{AOI} and β for *ST* and *RT* for June and December for N/S oriented solar modules. It is important to note that even with single-axis tracking, $\theta_{\text{AOI}} = 90°$ is achieved throughout the day for *RT* for both months, whereas $\theta_{\text{AOI}} = 0°$ is not achievable for both months, and the difference is much higher for December, which is due to sun's trajectory.

C. Calculation of Energy

For energy (I_{PV}) calculation, we first decompose global horizontal irradiance (I_{global}) into direct (I_{dir}) and diffuse (I_{diff}) irradiance [8], [10]. For irradiance collection on module from I_{dir}, θ_{AOI} is used [8]. Further, the energy harvested from I_{diff} or

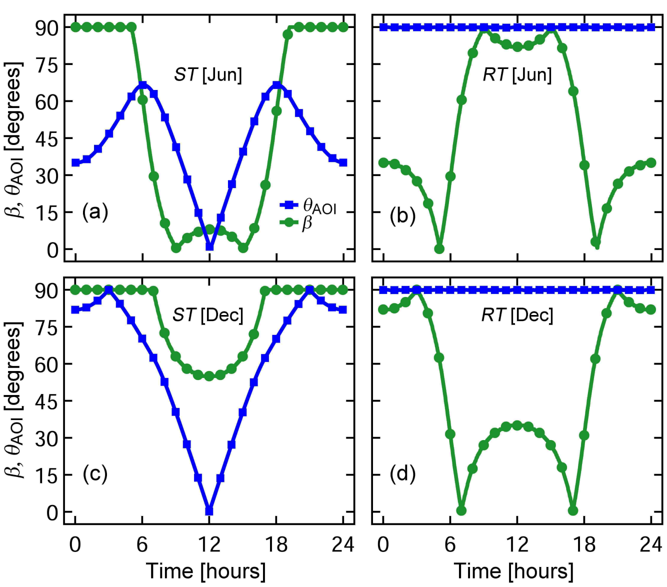

Fig. 2. Module tilt angle (β) and sun's angle of incident (θ_{AOI}) for N/S mounted solar modules for *ST* and *RT* tracking schemes for June and December.

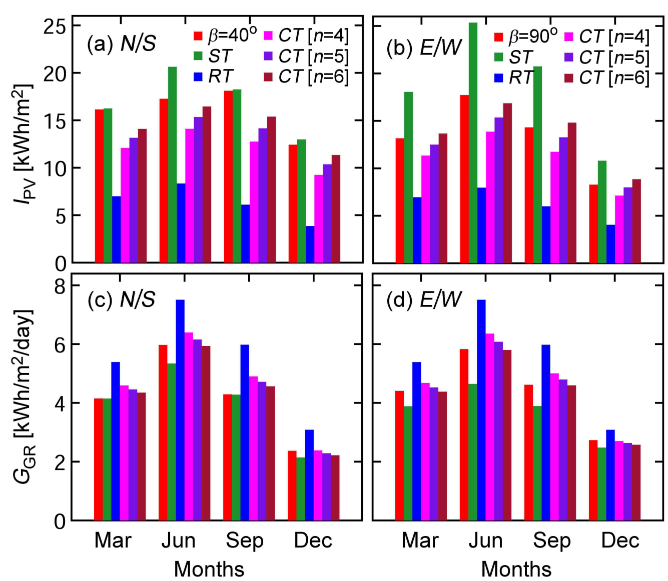

Fig. 3. Energy (I_{PV}) produced by PV modules and the global ground irradiance (G_{GR}) available for crops for different months for both N/S and E/W mounted modules for different tracking schemes for $p/h = 2$.

albedo, we use view factor approach as provided in [8]. A part of I_{diff} and I_{dir} reaches the ground and termed as the global ground radiation (G_{GR}). G_{GR} is the light available for crops and also used for albedo collection on the modules. The equations used for modeling of all the parameters are summarized in Table I.

III. Results and Discussion

Fig. 3(a) and 3(b) show I_{PV} produced per unit farm area by N/S and E/W mounted bifacial solar farm for different tracking schemes, whereas the corresponding G_{GR} is plotted in Fig. 3(c) and 3(d) respectively. The energy produced by *ST* is maximum for all months whereas the *RT* scheme shows the minimum I_{PV}. I_{PV} produced by different *CT* schemes depends upon n and lies within the range of I_{PV} produced by *ST* and *RT*. On the other hand, as shown in Fig. 3(c) and 3(d), G_{GR} is maximum for *RT* while minimum for *ST* for all months. It is important to note that *ST* for E/W mounted modules produce higher I_{PV} as compared to that for N/S mounted modules, for all months except for December. It is because the sun trajectory is more inclined towards south in December, which cannot be tracked by E/W mounted modules thorough single-axis tracking.

A. Effect of Pitch

It is reported that 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]. The required G_{GR} of PAR for different crops at their LSP is listed in Table II. In order to explore which tracking scheme best suits different seasonal crops by maintaining the required G_{GR}, we plot G_{GR} as a function of time for two different months (*i.e.* March, June) and for different module densities, *i.e.* different p/h values in Fig. 4 and Fig. 5. Module density is kept half (*i.e.* $p/h = 4$) and full (*i.e.* $p/h = 2$) for Fig. 4 and Fig. 5 respectively. The dotted lines in Fig. 4 and Fig. 5 represent G_{GR} at LSP for different crops.

TABLE II
G_{GR} of PAR required for different crops at LSP [11]

	G_{GR} [kLx]	G_{GR} [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

For $p/h = 4$ in Fig. 4, *ST* best suits for most of the crops for N/S facing modules whereas *RT* is the most suitable tracking schemes for crops that require higher PAR at their LSP (*e.g.* corn and Tomato) for both March and June. Similar behavior is seen for E/W facing modules for March. On the other hand, for E/W facing modules and for June, *CT* [$n = 6$] is suitable for most of the crops whereas *ST* results in lower G_{GR} than required at LSP of these crops during morning and evening. Similar to $p/h = 4$, *ST* best satisfies the LSP requirements for most of the crops for $p/h = 2$ in Fig. 5 for N/S facing modules during both March and June. For E/W facing modules, *ST*

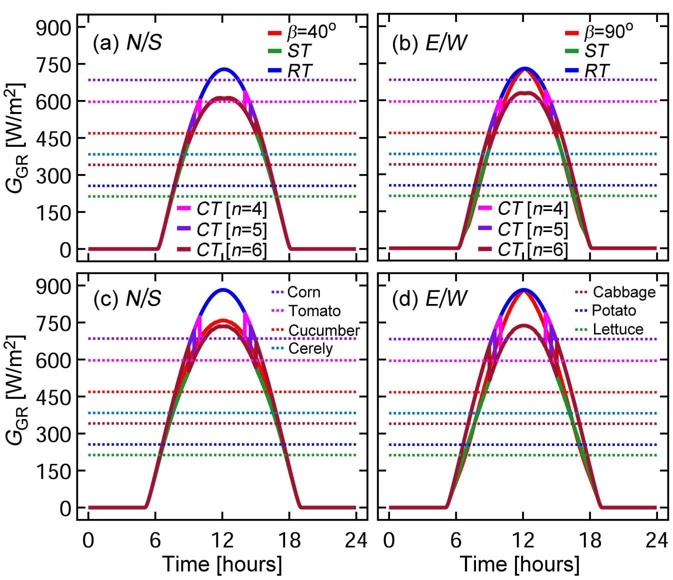

Fig. 4. Variation in G_{GR} over the day for N/S and E/W mounted PV modules for (a,b) March and (c,d) June for $p/h = 4$. Dotted lines represent G_{GR} required by different crops at LSP.

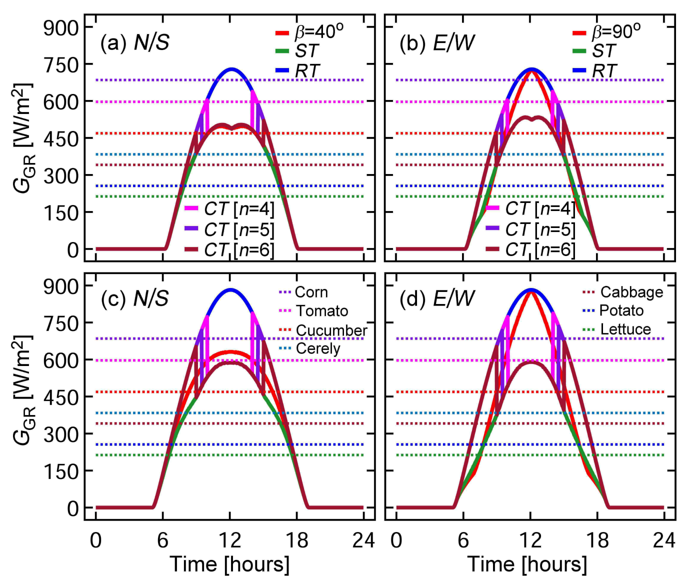

Fig. 5. Variation in G_{GR} over the day for N/S and E/W mounted PV modules for (a,b) March and (c,d) June for $p/h = 2$. Dotted lines represent G_{GR} required by different crops at LSP.

results in lower G_{GR} than required at LSP for all crops during morning and evening, therefore *CT* tracking schemes best satisfy the PAR requirements for all crops. The loss in G_{GR} for *ST* becomes more significant for June in E/W facing modules for all crops, and *CT* tracking schemes are the feasible tracking schemes for this scenario. Hence, Fig. 4 and Fig. 5 provide an insight how crop-specific *CT* could be developed for different PV module configurations.

IV. Conclusion

We have modeled the sunlight converted into solar energy and drop shadows of solar panels on crops as a function of time (with 1 minute resolution) for various solar tracking schemes at a given density of PV arrays. Suitable tracking schemes are evaluated for a variety of crops using the temporal variation of photosynthesis active radiation (PAR) incident on crops and the known values of saturated PAR for the crops. The tracking schemes are implemented in single-axis mode on bifacial PV arrays in East/West and North/South facing orientations. A method to extract the optimal tracking scheme for a given crop and PV array density is presented.

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] M. Z. Jacobson and M. A. Delucchi, "A path to sustainable energy by 2030," *Scientific American*, vol. 301, no. 5, pp. 58–65, 2009.

[3] 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.

[4] C. Dupraz, H. Marrou, G. Talbot, L. Dufour, A. Nogier, and Y. Ferard, "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.

[5] H. Dinesh and J. M. Pearce, "The potential of agrivoltaic systems," *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 299–308, 2016.

[6] "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," 2017.

[7] B. Valle, T. Simonneau, F. Sourd, P. Pechier, P. Hamard, T. Frisson, M. Ryckewaert, and A. Christophe, "Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops," *Applied Energy*, vol. 206, pp. 1495–1507, 2017.

[8] R. Younas, H. Imran, M. H. Riaz, and N. Z. Butt, "Agrivoltaic farm design: Vertical bifacial vs. tilted monofacial photovoltaic panels," *arXiv preprint arXiv:1910.01076*, 2019.

[9] 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.

[10] M. H. Riaz, H. Imran, and N. Z. Butt, "Optimization of pv array density for fixed tilt bifacial solar panels for efficient 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.