Techno Economic Modeling for Agrivoltaics: Can Agrivoltaics Be More Profitable Than Ground Mounted PV?

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Abstract—Agrivoltaics (AV) is a dual land-use approach to colocate solar energy generation with agriculture for preserving the terrestrial ecosystem and enabling food-energy-water synergies. Here, we present a systematic approach to model the economic performance of AV relative to standalone ground-mounted PV (GMPV) and explore how the module design configuration can affect the dual food-energy economic performance. A remarkably simple criterion for economic feasibility is quantified that relates the land preservation cost to dual food-energy profit. We explore case studies including both high and low value crops under fixed tilt bifacial modules oriented either along the conventional North/South (N/S) facings or vertical East/West (E/W) facings. For each module configuration, the array density is varied to explore an economically feasible design space relative to GMPV for a range of module to land cost ratio \( M_L \)—a location-specific indicator relating the module technology (hardware and installation) costs to the soft (land acquisition, tax, overheads, etc.) costs. To offset a typically higher AV module cost needed to preserve the cropland, both E/W and N/S orientated modules favor high value crops, reduced (\(<60\%) \) module density, and higher \( M_L (>25) \). In contrast, higher module density and an increased feed-in-tariff (FIT) relative to GMPV are desirable at lower \( M_L \). The economic trends vary sharply for \( M_L < 10 \) but tend to saturate for \( M_L > 20 \). For low value crops, \( \sim15\% \) additional FIT can enable economic equivalence to GMPV at standard module density. The proposed modeling framework can provide a valuable tool for AV stakeholders to assess, predict, and optimize the techno-economic design for AV.

Index Terms—Feed-in-tariff, land preservation cost, techno-economic model, vertical bifacial.

NOMENCLATURE

- \( A_{L,PV} \): GMPV land area.
- \( A_M \): Total module area including all rows.
- \( e_L \): Cost (per unit land area) related to land.
- \( \rho \): Overall food-energy profit for AV.
- \( e_L' \): Normalized land related costs.
- \( e_M \): Cost (per unit module area) related to module technology.
- \( d \): Depreciation rate.
- \( L/PV \): Photovoltaic.
- \( E/W \): East/West.
- \( FIT \): Feed-in-tariff.
- \( GMPV \): Ground-mounted photovoltaic.
- \( GW_P \): Gigawatt-peak.
- \( ha \): Hectare.
- \( HV \): High value crops.
- \( kW_P \): Kilowatt-peak.
- \( k \): Land preservation cost.
- \( LCOE \): Levelized cost of electricity.
- \( LER \): Land equivalent ratio.
- \( LPF \): Light productivity factor.
- \( LV \): Low value crops.
- \( m \): Module-to-land cost ratio.
- \( NREL \): National Renewable Energy Laboratory.
- \( N/S \): North/South.
- \( P_{AV} \): Annual energy profit for AV.
- \( PAR \): Photosynthetically active radiation.
- \( P_C \): Annual crop profit in AV ($/year).
- \( P_C\text{,fullsun} \): Annual crop profit under full sun ($/year).
- \( P_C' \): Normalized crop profit in AV ($/year).
- \( P_{GMPV} \): Annual energy profit for GMPV.
- \( P_{PAR} \): AV crop yield relative to full sun.
- \( P_{PARth} \): Normalized parameter quantifying the threshold crop yield for economic feasibility.
- \( P_{PV} \): Ratio of the annual energy produced per unit module area for AV to that for GMPV.
- \( YY_T \): Annual energy production.

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I. INTRODUCTION

The global agriculture requires a projected capacity to feed around 10 billion people by 2050 [1]. The preservation of agricultural lands, sustainable increase in crops’ yield, and protection against the climate change are some of the primary approaches to meet this global challenge. Similar to the growing food needs, the global energy consumption is predicted to increase by nearly 50% over the next 30 years [2], which necessitates an enormous growth in the renewable energy generation, including solar and wind, to save the climate. Sustainable food-energy solutions also require an effective use of the land to preserve the terrestrial ecosystems and biodiversity. The conventional ground mounted photovoltaic (GMPV) systems are not typically designed for the utilization of their covered arable land area for conventional agricultural production. As the global GMPV installations are increasing rapidly, concerns over the land use change, food security, and biodiversity preservation are continuously on the rise [3], [4], [5], [6]. Moreover, with falling prices for solar power technology and increasing pressure of climate vulnerabilities, farmers in many countries are tempted to convert their agricultural land into GMPV [7].

An innovative approach to address these issues are the dual land usage systems called agrivoltaics (AV), which have recently gained a widespread popularity [8], [9]. An AV system utilizes the same land for the dual production of crops and energy by elevating the panels above ground and configuring them to facilitate agricultural operations [10]. The concept of AV was initially proposed by Goetzberger and Zastrov back in 1981[11]. During the last decade, many academic and commercial scale AV installations [12], [13], [14], [15], [16] have been reported that indicate attractive synergies for the food-energy-water nexus including a higher water use efficiency, increased yield for the selected crops, and a cooling effect for solar module resulting in higher energy yield. In many countries, government policies also support AV and currently ~2000 AV systems with cumulative capacity of 2.8GWp have been installed across the globe [12], [13], [14]. Many field studies and modeling work have also been reported for assessing and predicting the performance for different AV module configurations and crops [17], [18], [19], [20], [21], [22]. Some of the common AV module configurations are shown in Fig. 1 with a comparison with typical GMPV. While a win–win situation for food-energy attracts a lot of interest for AV, its economic feasibility for all the stakeholders including PV investors, farmers, and policymakers is critically important for its widespread acceptability. In recent years, significant research efforts have been reported on AV module technologies, crop-specific field experiments, and food-energy yield modeling [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23]. Although more work is needed along various technological dimensions, e.g., to understand how different plant species adapt under PV shading for different climates, and the crop response as a function of water availability and light quality, etc., a detailed technoeconomic modeling requires a simultaneous attention. In particular, the economic tradeoffs as a function of various module configurations, land-specific costs, energy tariffs, and crop profits have not been modeled in comparison with GMPV. The installation of AV modules is typically more expensive as compared to GMPV due to an elevated mounting and customized foundations that are typically needed to facilitate agricultural operations on the same land [24].

A higher levelized cost of electricity (LCOE) for AV as compared to GMPV is therefore considered to be the land preservation cost for the AV system [12]. A recent study by NREL [26] estimates the land preservation costs for AV to be 50% to 20% of the premium costs of the GMPV for the N/S faced fixed tilt and the vertical E/W faced systems, respectively. Despite a higher LCOE, an additional revenue from crops can make AV economically superior to GMPV provided it could offset the land preservation cost. A recent field study [12] compares the economic performance of a 194.4 kWp AV system, which grows potatoes and winter wheat with GMPV. A simple model that is based on price-performance ratio is used to evaluate the economic performance, where the price is the land preservation cost, and the performance benefit comes from the crop revenue. The AV modules which are elevated 5 m above the ground results in 38% higher LCOE in comparison with GMPV. The revenue from potatoes is shown to be high enough to offset the increase in LCOE, making AV more profitable than GMPV although the biomass yield for potatoes drops to ~87% for AV as compared to the full sun condition. The revenue from the winter wheat is however significantly lower, which could not compensate for the land preservation cost for AV. Although this modeling approach is useful, the focus of the study is limited to the given field experiment and the effect of varying the module design, land costs, and FIT are not explored.

In another recent study [27], an analytical framework determining the economic benefits and adoption potential of AV has been proposed. The economic performance for AV is evaluated from the perspective of maintaining the farmer’s profitability with respect to the conventional agriculture farm. While the model applies well to the farmer’s economic perspective, it does not explore the solar investor’s profitability, in particular, the impact of land preservation cost on the solar energy profit and the economic performance of AV relative to the conventional GMPV. The economic performance for AV relative to GMPV and roof-top PV is explored in [24] under a set of economic assumptions. The study reports that GMPV systems are about 33% cheaper than AV due to halved costs for installation, balance of plant and support infrastructure but the net present value for AV could generate more profit toward the end of the project lifetime. The potential of rainfed AV for ground water stressed irrigated regions across the world is studied in [28] by integrating solar, crop, hydrology, and financial models. A simulation-based study reported in [29] shows the advantage of AV over the traditional farming systems, which rely on diesel engine for irrigation. The efficient usage of land is also demonstrated by calculation of land equivalent ratio.

Even though the reported economic studies on AV demonstrate important trends and case studies, there is a lack of a...
systemic technoeconomic evaluation that could quantify the relationship between the module array configurations and the food-energy economic performance. The module array configurations are designed in many cases from the perspective of maximizing food-energy yields [17], [19], [20]. This is often determined using metrics such as land equivalent ratio (LER) and light productivity factor (LPF) [19]. The best module configurations for maximizing LER or LPF might not be the most economically feasible from the perspective of PV investor. A holistic model is needed to explore the effect of varying AV module configurations under a broad range of economic factors including the soft land costs, which can widely vary on local as well as global scales and the module related system costs which have a lesser location dependence but can strongly vary as a function of the module technology and system configuration. Moreover, in contrast to the conventional food-energy systems, where standard parameters such as LCOE and farm profits are routinely used, useful metrics to quantify the combined food-energy economic performance are lacking for AV which makes the system design optimization difficult.

In this article, we present a technoeconomic model based on convenient metrics to quantitatively explore the relationship of module array configurations with the economic performance for AV as a function of technology-specific land preservation costs, crop income, energy tariffs, and land-specific soft land costs. For the first time, this study presents a systematic approach to explore:

i) how the module array density for AV affects its overall economic performance?

ii) what profit margins (crop rotations) could offset the land preservation cost?

iii) how does the economic performance vary with the location specific costs including land acquisition, overheads, and taxes?

iv) what is the economic threshold to invest on AV infrastructure to preserve an agriculture land for a given crop and location?

v) what is the minimum adjustment in FIT if a given AV system needs to meet the economic equivalence to GMPV?

vi) what is an optimal design space for the module arrays in terms of spatial density to maximize the economic performance? All these questions are explored for bifacial modules in the traditional N/S faced fixed tilt as well as vertical E/W faced configurations.

The rest of this article is organized as follows. In Section II, we report the methodology and mathematical modeling of this technoeconomic framework highlighting its major assumptions and components. In Section III, we apply the framework to assess the economic feasibility of AV for two different orientations (N/S and vertical bifacial E/W) across two simulated crop rotations for Khanewal located in Southern Punjab, Pakistan. Section III-A discusses questions (i)—(iii) as mentioned in the preceding paragraph and Section III-B discusses questions (iv)—(vi). Finally, Section IV concludes this article.

II. MATHEMATICAL MODELING

A. Basic Economic Model

While comparing the relative economic performance for AV with GMPV, the basic premise of the model is that the land preservation cost needs to be offset by the net food-energy profit from the land. Additional constraints such as the minimum threshold yield for the crop production could further be applied. The extra costs incurred for AV due to a customized mounting need to be offset by additional revenue generated from crops:

\[ P_{AV} + P_c \geq P_{GMPV} \] (1)

where \( P_{AV} \), \( P_{GMPV} \) are the annual energy profit from AV and GMPV, respectively, and \( P_c \) denotes the profit from crops in $/year. Similarly, from the crop’s perspective, any loss in the AV crop yield relative to the full sun condition needs to be balanced by the energy profit

\[ P_{AV} + P_c \geq P_{c_{full\_sun}} \] (2)

where \( P_{c_{full\_sun}} \) denotes the profit from crops in full sun condition in $/year. An investment on AV can be economically attractive when (1) and (2) are both satisfied. In most practical cases worldwide, the annual profit per unit land area from solar energy can be significantly greater than the annual profit per unit land area from agriculture [30], [31]. We therefore assume that (1) implies (2) and focus on exploring conditions that could satisfy (1). It is implicit that the overall profit of AV [left-hand side of (1) and (2)] is of interest in our approach rather than the individual energy and food profits while assuming that the yields do not drop below the limits imposed by local policy.
Maximizing the overall food-energy profit is best applicable for the case when a single entity owns the revenues from $AV$ energy and the agricultural production. If, however, multiple stakeholders own the food and energy profits, bilateral contracts, and the government policies could be defined to ensure the mutually agreed profitability of the individual entities in support of the land preservation. Future work is needed to explore various scenarios in this context.

We can express the energy profit in the form of feed-in-tariff (FIT), LCOE, and annual energy production ($YY_T$) in (1)

$$(FIT_PV - FIT_{AV} + LCOE_{AV} - LCOE_{PV}) \times YY_T \leq PC$$

where the subscripts $AV$ and $PV$ denote the agrivoltaics and GMPV systems, respectively. We assume an identical annual energy generation capacity for $AV$ and GMPV. Depending upon the $AV$ module configuration, this may result in different land and module areas for $AV$ versus GMPV. We will discuss the case of different FIT for $AV$ and GMPV in the next section. Here we assume that there is no difference in the FIT, so we can write

$$(LCOE_{AV} - LCOE_{PV}) \times YY_T \leq PC.$$  (4)

We can express LCOE as [32]

$$LCOE = \frac{cM \cdot AM + cL \cdot AL}{YY \cdot AM \cdot \chi} = \frac{ML + p/h}{YY \cdot \chi/cL}$$  (5)

where $c_M$ is cost (per unit module area) related to module technology (including balance of system), and $c_L$ is soft cost (per unit land area) related to the land (including overhead, developer profit, and taxes). These costs include both capital and the operational costs (excluding the residual values) evaluated over the lifetime. $A_M$ refers to the total land area covered by modules and $A_L = N \times L \times h$ is the total physical area of the modules including all rows ($N$), where $L$ is the length of a single row of modules, and $h$ is the physical dimension of the modules normal to ground. $YY$ is the annual energy production per unit module area and $p/h$ is a design parameter representing the module array density where $p$ is the pitch (row to row distance). $M_L = c_M/c_L$ is a unitless quantity, which is the ratio that depicts the effective costs related to the module technology to that related to the location specific soft costs for the land. Since the latter can vary widely across geographical locations and can strongly depend on local policies, $M_L$ can have a broad range. Typically reported values of $M_L$ in US ranges between 10 – 20 for GMPV [12], [24], [32]. Globally, reported values of $M_L$ for GMPV ranges between 5-15, but due to the typically higher infrastructure requirement for $AV$, $M_L$ is expected to be higher for $AV$ in comparison with GMPV [33].

$$\chi = \sum_{k=1}^{\infty} (1 - d)^k (1 + r)^{-k},$$

where $d$ and $r$ are depreciation rate and discount rate, respectively. $c_M$ for a specific GMPV technology does not change significantly across global locations (slight variations are possible due to the local policies related to taxation, import, material costs, and labor). $c_L$, on the other hand, can vary significantly across locations, both across the country and on global scales depending upon the type of the land, (e.g., urban versus rural), soil fertility, and water availability, etc.

We can rewrite (4) by dividing $LCOE_{PV}$ on both sides and simplifying using (5)

$$\left(\frac{M_L + \frac{p}{h}}{M_L + \frac{p}{h}}P_{PV}\right) \times \frac{1}{YY_{PV}} \leq \frac{PC}{(M_L + \frac{p}{h})P_{PV} \times \left(\frac{cL}{\chi}\right) \times AM} + 1.$$  (6)

After simplifying (6), we get (see appendix)

$$\left(\frac{CM}{C_{M, PV}}\right) \defeq \kappa \leq \alpha \cdot P_C \cdot \chi - \left(\frac{1}{YY} - \frac{AL_{PV}}{AL_{AV}}\right) \alpha \cdot c_L + YY_{PV}.$$  (7)

where $\kappa$ is the ratio of module related costs for $AV$ relative to that for GMPV and represents normalized crop profit and land related costs. Defining $\rho \defeq P_C' - c_L' + YY_{PV}$, respectively, we can write (8) as

$$\kappa \leq \rho.$$  (9)

where $\rho$ represents the overall food-energy profit for $AV$.

Equation (9) is a key result of this article. The criterion in (9) can be used to evaluate the technoeconomic feasibility of $AV$ relative to GMPV for a range of scenarios including a variety of land costs, crop rotations, and module configurations. $\kappa$ is usually $\geq 1$ due to a customized foundations and elevated AV mounting structure. A threshold $p (\rho_{th})$ can be defined for the case of equality in (9) to ensure that the land preservation cost is balanced by the food-energy profits. For a given module system, $\kappa$ can serve as an input parameter in (9) and $\rho_{th} = \kappa$ can be sought to ensure economic equivalence to GMPV. In general, the $AV$ design including suitable crops and module configurations can be optimized to maximize $\rho$ above $\rho_{th}$. For the case when the crops are preselected and land costs are known at the design stage, $\rho$ can be estimated as the model input and a threshold $\kappa (\kappa_{th} = \rho)$ can be defined to be sought by optimizing the module technology. The land preservation cost or the margin for an extra investment on $AV$ module technology relative to GMPV is then equal to $(1 - \rho) \times 100\%$.

Since $\kappa$ is above 1 in most practical situations, the relative economic feasibility for $AV$ does not hold for $\rho < 1$. The economic feasibility criterion in (9) implies that the cultivation of high value crops under $AV$ system is desired. In addition, an optimal choice of $p/h$, a cost-effective design for the elevated module infrastructure, and the selection of land, are important. Different module configurations and crop rotations have been evaluated in
the literature for $AV$ systems. The mounting structure cost can significantly vary due to different elevation, choice of materials, and the design of foundations. The practical value of $\kappa$ therefore depends upon specific economic details for a given $AV$ design. For example, $\kappa$ derived for $\sim$5 m elevated mounting installed in Germany is about 1.38 [12]. For vertical $E/W$ oriented $AV$ systems, $\kappa$ is typically lower as the minimum ground coverage of the modules allows a significantly lower elevation while still preserving most of the agricultural land. The value of $\kappa$ for vertical $AV$ from a field experiment could not be found in the literature. A recent estimate from NREL [26] however estimates 20% increase in the premium costs for vertical $AV$ as compared to GMPV. The precise value for $\kappa$ could however vary depending upon the actual need for elevation based upon the height of the intended crops. In this study, we assume that $\kappa = 1.2$ for $E/W$ vertical bifacial $AV$, i.e., 20% higher relative to GMPV. The qualitative findings of this article however remain applicable for any value of $\kappa$ and are hence useful for any practical system design.

B. Effect of Feed-in Tariff (FIT) and Production Profiles

When the government policy allows for a higher FIT for $AV$ relative to GMPV, we can add a factor of $\Delta FIT = FIT_{AV} - FIT_{PV}$ into (4) and get an equation analogous to (8)

$$\kappa \leq P'_e - c_L + Y_{PV} + \frac{\Delta FIT}{\beta}$$

(10)

$$\Delta FIT \geq \beta \times (\kappa - \rho)$$

(11)

where $\beta = c_{M_{PV}} \times (1 - \Delta V_F) / (YY_{AV} \times \chi)$ and $\Delta V_F$ is the percentage change in the value factor ($V_F$) for vertical $E/W$ faced $AV$ versus standard $N/S$ faced GMPV. The metric $V_F$ captures the economic effect of variation in the daily production profiles for power plants [34]. The production profile for vertical $E/W$ has unique morning/afternoon peaks [20] that may influence its relative economic gain in some electricity markets as compared to the standard $N/S$ faced fixed tilt systems. $V_F$ for a power plant is defined as the ratio of the specific (time-weighted) revenue of the plant to the average (time-weighted) market price (base price) [35]. Any value of $V_F$ greater than 1 represents the case when the $PV$ generation profile allows to benefit from higher market prices. A recent study [34] explored this effect for European markets and showed that the relative economic benefit for $E/W$ vertical versus $N/S$ tilted configurations in terms of the difference in production profiles varies across markets depending on the day-ahead electricity prices, the overall market penetration of $PV$, and the latitude. When the market price is almost flat (as in the case for Bergen, Norway), vertical $E/W$ achieved nearly the same $V_F$ as compared to $N/S$ tilted. In contrast, for Germany, a country with a significant amount of installed $PV$ capacity, vertical $E/W$ reached a relatively higher $V_F$. For Pakistan where the electricity markets are still under development and the electricity prices remain flat throughout the day, we assume $\Delta V_F = 0$. However, the model has the flexibility to incorporate any $\Delta V_F$ as needed for any specific energy market.

The threshold feed-in tariff ($\Delta FIT_{th}$) is defined when the equality holds for (11). $\Delta FIT_{th}$ is proportional to the module technology costs per unit energy produced and depends on the difference between $k$ and $\rho$, which makes it highly dependent on the system design including modules’ orientation, array density, and the land costs. $\Delta FIT$ can be used as a tool by the policy makers to support agricultural land preservation through $AV$. Moreover, $\Delta FIT$ can be made crop-specific if cultivation of some selected crops needs to be promoted at a given location.

C. Economic Condition in Terms of Crop Profit

We can rearrange (10) to define a criterion for crop profit

$$P_c \geq \left[ c_{MAV} \left( 1 - \frac{Y_{PV}}{k} \right) + c_L - \frac{\Delta FIT}{YY_{TV} \times \chi} \right].$$

(12)

The above criterion signifies that $AV$ crop profit needs to compensate the higher $AV$ module technology costs and the given land cost while a higher FIT for $AV$ can allow the crops having relatively low value to be economic feasible. Defining $P_c ^{\text{def}} = Y_{PAR} \times P_c ^{\text{full sun}}$, where $Y_{PAR}^L$ is the relative biomass yield for $AV$ versus that under the full sun condition. For simplicity, we assume $Y_{PAR}^L$ to be equivalent to the ratio of total sunlight received by the crops under $AV$ relative to the full sun condition [19], [20], [23]. We can rewrite (12) as

$$Y_{PAR}^L \geq Y_{PAR}^L$$

(13)

where $Y_{PAR}^L$ represents the normalized threshold crop yield required to offset the additional $AV$ costs related to modules and land (minus any adjustment due to $\Delta FIT$).

The criterion for $Y_{PAR}$ in (13) provides a simple measure for selecting crops with an appropriate market value to meet an economic equivalence with respect to $GMPV$ at a given FIT, and the costs related to modules and land. Moreover, it allows us to estimate an upper bound to the biomass yield loss that can be economically tolerable for $AV$. It is worth noting that $Y_{PAR}^L$ is normalized to the crop profit, which implies that the high value crops are more likely to meet the criterion in (13) as compared to the low value crops. It also confirms that the crops, which have relatively small loss in biomass yield under the module shades are preferable. For a given $AV$ system, farmer and policy makers can negotiate $\Delta FIT$, which could satisfy (13) for the desired crop.

D. Calculation of Energy and Crop Yields

The model to simulate the module energy generation and the $PAR$ available to the crops under the modules is explained in our previous papers [19], [20]. Here, we briefly describe the approach. Assuming a relatively large size module arrays and ignoring the effects at the edges of the arrays, we solve for the shading patterns in two spatial dimensions, i.e., perpendicular to the length of the arrays and the height above the ground. A view factor model which has been previously validated on field experiments [19], [20], [32] calculates the sunlight intercepted by the modules to get the temporal $PV$ yield, which includes the contributions from direct beam, diffused light, and albedo (both direct and diffuse components). The shading for the direct
and diffused light is calculated for the 2-D planes along the vertical direction below the modules to find the \( PAR \) incident on crops. Typical meteorological conditions for Khanewal, Punjab, Pakistan \((30.2864^\circ N, 71.9320^\circ E)\) are used \([32, 36]\). The analysis and simulations are performed for \( N/S \) faced 30° fixed-tilt and \( E/W \) faced vertical bifacial modules. Different \( AV \) farm schemes based on \( N/S \) faced fixed tilt and \( E/W \) faced vertical bifacial along with conventional Ground Mounted \( PV \) (GMPV) systems are shown in Fig. 1 with height \((h)\) and pitch \((p)\) labeled.

The average income/profit for the conventional agriculture is taken from Zhang et al. \([36]\) for the year 2018 for Khanewal \( P_c = Y_{PAR} \times P_{cb} \). The crop yield loss due to shading is calculated based on the drop in the useful \( PAR \) received by the crop across the day. The daily useful \( PAR \) is calculated by taking the daily integrating of the \( PAR \) received by the crop up to its light saturation point. The daily yield ratio, \( Y_{PAR} = \frac{PAR_{u, full\ sun}}{PAR_{u, AV}} \), where \( PAR_{u, AV} \) and \( PAR_{u, full\ sun} \) are the daily useful \( PAR \) for the \( AV \) and the full sun condition, respectively. The crop yield for \( AV \) is then calculated as: \( Y_{c, AV} = Y_{PAR} \times Y_{c, full\ sun} \). We have previously shown that this method shows a reasonable match with \( AV \) field experiments \([19, 20]\). It should however be noted that this approach does not consider any synergistic effects of shading on crop yield (e.g., increase in crop yield with shading for certain climate/crops under hot/arid conditions as has been reported in \([8]\)). The approach used here can therefore be considered an upper limit for crop loss due to \( AV \) shading. Nevertheless, the overall economic framework presented here is generic and can be used with any crop yield model or actual field data for crop yield.

### III. Results and Discussions

The modeling framework is applied for two conceptual \( AV \) farms: (a) high value, and (b) low value farms represent crop rotations that yield high and low annual profit, respectively, for Khanewal \((30.2864^\circ N, 71.9320^\circ E)\), Punjab, Pakistan. Each farm is studied under conventional \( N/S \) faced fixed tilt and \( E/W \) faced vertical bifacial module orientations. The cropping cycle and reported crop yield/revenues for Khanewal are taken into consideration while simulating the low value and high value farms. Crop rotation for the high value farm comprises of tomato, cauliflower, and garlic over the year, while for the low value farm, it consists of wheat and cotton as shown in the Appendix (Tables I and II, respectively).

#### A. Effect of Module Density, Land Costs, and Crop Profits

In this section, we explore the economic trends assuming that there is no difference in \( FIT \) between \( AV \) and GMPV. Fig. 2 shows the effect of module array density on the economic performance for both \( N/S \) and \( E/W \) faced \( AV \) orientations under different \( M_L \). The reported values for \( \kappa \) (as discussed in the Section II) are shown by dotted lines. The variation in \( \kappa \) due to change in system installed cost with \( p/h \) variation for the \( N/S \) faced orientation is depicted in the positive slope of the dotted line representing \( \kappa \) \([26]\). For \( E/W \) vertical orientation, the change in system installed cost with varying \( p/h \) is assumed negligible as shown in the dotted straight lines in Fig. 2(c) and (d). The normalized food–energy profit is illustrated by \( \rho \) that is evaluated using \((9)\) and the economic implications of module array density and land costs are studied through varying \( p/h \) and \( M_L \). For the high value farm (Fig. 2(a), the trend for \( \rho \) versus \( p/h \) changes from a negative to a positive slope as \( M_L \) is increased. An intermediate behavior is found at \( M_L \sim 10 \), for which \( \rho \) first increases with \( p/h \), maximizes at \( p/h \sim 3 \), and then shows a downward trend. Higher \( p/h \) implies more land area under \( AV \), which allows an increased crop revenue. On the other hand, higher \( M_L \) implies reduced land related costs which favor the use of more land area, i.e., higher \( p/h \). Fig. 2(a) shows that the economic equivalence for \( AV \) with respect to GMPV can be obtained by matching the food-energy profit to land preservation cost (i.e., \( \rho_{th} = k \)). This condition is met for \( N/S \) high value farm when \( M_L \) is between 30—50 at \( p/h \) of \( \sim 5.5—6 \). For the low value farm \( [\text{see Fig. 2(c)}] \), the trend for \( \rho \) versus \( p/h \) shows a negative slope for all \( M_L \), which prevents the food-energy profit to meet the land preservation cost for the entire range of \( p/h \). For both types of farms, there is a specific \( M_L \) (10 and 50 for high and low value farms, respectively) close to which the food-energy profit does not change much with \( p/h \). This happens when the higher land related costs balance with the higher crop revenue as the land area is increased by lower module density. These trends highlight the quantitative economic significance of the module density and tradeoffs between land preservation cost,
soft land costs, and crop profits. The land preservation cost for AV, i.e., $k$ can potentially lower in future with innovations in the technology for AV modules, structures, and foundations, that can quantitatively shift the thresholds for the economic feasibility in Fig. 2 toward a lower $p/h$.

The trends for E/W faced vertical bifacial orientation are shown in Fig. 2(b) and (d) and are qualitatively similar to that for N/S faced AV configuration. Here, the value of $\kappa$ is lower as compared to the N/S faced orientation as discussed in Section II-A.

Moreover, since more daily light intensity is available to crops in E/W vertical as compared to the N/S tilted orientation at the same $p/h$ (see Fig. 10 in the appendix), a relatively higher crop yields are possible in E/W vertical system for a given module density. This however has a tradeoff with the annual energy generation, which is generally lower for the E/W vertical in comparison with N/S faced fixed tilt AV systems [17]. Fig. 2(b) shows that the economic equivalence ($\rho_{th} = k$) with respect to GMPV can be obtained for E/W HV farm when $M_L$ is above 30 and $p/h$ is $\sim$5—6. For E/W LV farm [see Fig. 2(d)], however, the economic equivalence is not approachable even at higher $p/h$ and $M_L$, which resembles with the case of N/S faced LV farm. One of the important benefits of E/W vertical orientation is the homogeneity of the daily cumulative sunlight over the crops [23]. A comparison for sunlight over the crops across the pitch for the vertical E/W and N/S faced AV configurations is shown in Fig. 12.

Fig. 3 explores the economic feasibility of AV from the perspective of relative crop yield. The relative crop yield for AV (indicated by $Y_{PAR}$) and the threshold crop yield (indicated by $Y_{PARb}$) are compared for HV and LV systems at different $M_L$, for high value (top) and low value crops (bottom). The economic criterion is satisfied for the high value crops for $p/h \geq 5$ when $Y_{PAR} \geq Y_{PARb}$. For low value crops, the criteria far exceed the crop yield for both module configurations.

Fig. 3 Normalized threshold crop yield ($Y_{PARb}$) and effective AV crop yield modeled as $Y_{PAR}$ relative to the full sun condition for N/S fixed tilt and E/W vertical bifacial AV orientations at different $M_L$, for high value (top) and low value crops (bottom). The economic criterion is satisfied for the high value crops for $p/h \geq 5$ when $Y_{PAR} \geq Y_{PARb}$. For low value crops, the criteria far exceed the crop yield for both module configurations.

Fig. 4. Effect of $M_L$ on the normalized food-energy profit ($\rho$) for N/S fixed tilt and E/W vertical bifacial orientations for constant $p/h = 3$ is shown for high value and low value crops. The dotted lines represent the land preservation cost ($\kappa$) for each module configuration. At higher $M_L$, $\rho$ increases until it saturates for $M_L > 30$. It can be noted that the economic criterion ($\rho \geq \kappa$) is not satisfied at any $M_L$ at the selected $p/h$ for both module orientations.
B. Effect of Feed-in Tariff (FIT)

Until now, we have assumed an identical FIT for AV and GMPV. In practice, government policies may allow a higher FIT for AV to promote the land preservation. We now explore how ΔFIT can modify the trends shown in the previous section. Fig. 5 shows the effect of ΔFIT on ρ for p/h = 3 and ML = 20. As expected, a linear behavior between ΔFIT and ρ is observed. We can compute ΔFIT_th for each of the module orientations and crop rotation by looking at the intersection of ρ and the respective values of κ (shown as dotted horizontal lines at for N/S and E/W faced orientations, respectively) taken as the inputs. ΔFIT_th is the lowest for the HV farm in N/S faced orientation closely followed by the HV farm in the E/W vertical orientation. For the LV farm, a higher policy incentive in the form of a higher ΔFIT_th is required for making AV system economically equivalent to GMPV. ΔFIT_th for the HV farm is significantly lower as compared to that for the LV farm due to a large difference in the profits obtained from crops. The difference between ΔFIT_th for the N/S vs E/W orientations for the same crop rotation is however not as large.

It is however worth mentioning that E/W vertical orientation may have additional benefit due to its unique morning/afternoon peaks, which can provide a higher market value relative to N/S faced orientation in some energy markets [34] as represented by ΔVF in (10). For the scope of this study, we have taken ΔVF = 0 as explained in Section II but future studies can explore this effect for energy markets where ΔVF may be significant.

Fig. 6 shows the impact of ML on ΔFIT_th for N/S fixed tilt and vertical E/W bifacial orientations for AV for high value and low value crops at p/h = 3. ΔFIT_th reduces as ML is increased until it saturates around ML > 30.

C. Design Space for Economic Feasibility Relative to GMPV

Based on the trends shown in Figs. 2, 3, 4, 5, and 6, we now identify an economically feasible design space for AV systems for the two crop rotations and module configurations as a function of module to land cost ratio. Figs. 7 and 8 show contours of ρ and ML, respectively, as a function of ML and p/h for HV and LV farms for cases without and with ΔFIT, respectively.
The economic performance for AV becomes equivalent or better than GMPV when \( \rho \) equals or exceeds the given \( \kappa \) specified by the module technology. It is evident from Fig. 7 that for HV farm, \( \rho \geq \kappa \) is achieved at \( p/h \sim 6 \) and \( M_L \geq 50 \) for N/S, and \( p/h > 5.5 \) and \( M_L \geq 30 \) for E/W, as highlighted by insets in Fig. 7. For LV farm, on the other hand, no economically viable design space can be observed due to the low income from crops. It is worth noting that the practical \( M_L \) values for GMPV are reported in the range of 10–20 [12], [24], [32] for which \( p \geq \kappa \) is not attainable even for the HV farm. This implies the need for \( \Delta FIT \) under these situations.

Since it is evident from Fig. 7 that there is no economically viable region for the LV farm relative to GMPV while the HV farm may also underperform for some of the practical ranges of \( M_L \), AV requires a contribution in the form of \( \Delta FIT \) to be economically viable under these scenarios. Fig. 8 shows \( \Delta FIT_{th} \) required for HV and LV farms in N/S and E/W configurations for achieving economic equivalence with respect to GMPV as a function of module density and land costs. The insets in Fig. 8 show zoomed view for \( \Delta FIT_{th} \) in the \( p/h \) range of 3–5 and \( M_L \) of 5–35. A higher \( \Delta FIT_{th} \) is required for lower crop income and it also varies with land related costs and \( p/h \). \( \Delta FIT_{th} \) required for different module configurations, array densities \( M_L \), and crop rotations are summarized in Table III (see Appendix). \( \Delta FIT_{th} \) can serve as an important economic input for AV designers and investors while selecting the module technology, array configurations, and crops. Similarly, policymakers can make it attractive to cultivate some specific set of crops at a given location by offering crop-specific \( \Delta FIT \) for different locations and module configurations. Future studies are needed to explore such cases in detail across various countries in the world.

D. Limitations and Future Extensions

Although the general criterion described in (9) and (13) is accurate, following assumptions are made in deriving the inequalities. First, the energy profit is assumed to be higher than the crop profit per unit land area, which is often the case for AV systems. Second, the response of the crop yield to the partial shading is based on the spatial-temporal light sharing (LPF) model described in [19]. The LPF model nicely models the intraday light fluctuations under the AV shades but ignores the effects of water or nutrients stress and any shade related physiological adaptation by the crop. Nevertheless, the model provides a very convenient way to do a first-order analysis especially when the purpose is to compare a variety of module configurations and other system variables. Finally, the model evaluates the economic feasibility assuming that the energy and food profits are owned by the same entity. This may be valid when a farmer owns the solar investment or vice versa but this does not need to be always the case. If the solar investor and the farmer are separate entities, the profits from energy and crop, and the land related costs need to be distributed among them according to the business deal. Policy interventions from the government become much more important under these scenarios and can strongly influence the technoeconomic design space. Extensions of our model are planned to cover such scenarios and will be a part of future research.

Future studies are planned to extend the application of this modeling framework to other crop rotations along with exploring the tracking module configurations. Tracking allows reduction of height as it would allow farm equipment movement by tilting away from the combine harvesters. The shadow-depth is also reduced and energy yield increases significantly [37]. Therefore, it can change the economics of AV in important ways.

Our results emphasize the need for AV synergies that increase the farm yield. The access to solar energy generation on agricultural land should be restricted to AV that farmers accept on their land without land lease to maximize synergies and services to increase agricultural yield. More research is needed to identify the agricultural impact (and benefits) across various climates/crops. The potential to solve challenges regarding excess of irradiation and water stress can be one of the highest benefits that AV could enable for countries with sunny warm climate and water shortages.

IV. CONCLUSION

In this article, we have presented a technoeconomic modeling framework to assess and predict the economic performance of AV systems relative to the standard ground mounted PV. The effects of module design configurations including array density and orientation, income from crop, technology specific and land related costs, and FIT are explored. To support cropland preservation, AV typically has a higher module technology...
cost as compared to standard PV primarily due to elevated mounting and customized foundations that can potentially make it economically nonattractive for PV investors. We show that it is possible to design an economically attractive AV system by selecting a suitable crop rotation and module configuration for the given land related costs and FIT. The model is applied to compare the relative economic performance of fixed tilt N/S versus E/W faced vertical bifacial modules at various module densities for two selected crop rotations that represent high and low profit margin crops for southern Punjab, Pakistan. Following conclusions are made based on the modeling results:

1) To offset the land preservation cost for AV, module arrays at a reduced (~one-third) density are economically favorable with the high value crops when the land costs are relatively lower than the module costs (i.e., \( M_L > 20 \)). The crop biomass yield loss remains small under this situation because of low shading.

2) For low value crops, reducing the module density is not economically desirable even when land costs are small. This implies that the standard module density can be the appropriate choice provided the crop biomass yield does not drop below an acceptable limit defined by the local policy.

3) E/W faced vertical module configuration can although be less productive in terms of annual energy production, its overall economic performance can match closer to the standard N/S faced modules due to its lower land preservation cost. Moreover, vertical configuration provide a much better shade homogeneity for crops. Secondary benefits (not quantified in this study) for the vertical configuration include minimum ground coverage, negligible soiling loss, and potential to benefit from morning/afternoon peaks in energy markets, that can be additional merits when making the technology choice.

4) For high value crops and low land costs, AV can provide equivalent profitability relative to the ground mounted case without needing a higher FIT. When the crop profit is low, a moderate increase (~10% for the case studied here) in FIT is however needed for AV for economic equivalence.

5) When the land costs are high and approach closer to the module costs (i.e., \( M_L < 10 \)), AV economic performance shows a high sensitivity to \( M_L \). This trend tends to saturate above \( M_L \sim 20 \).

6) The design space for AV to be economically equivalent to ground mounted system without a higher FIT for both (E/W and N/S) module configurations needs \( p/h \sim 5 \), high value crop, and \( M_L > 20 \). As FIT is increased (~10%) relative to that for the ground mounted system, low value crops, smaller \( p/h \), and smaller \( M_L \) can be economically feasible.

In summary, this study finds that higher balance-of-system costs due to the land preservation for the cropfield plays an important role in the AV economics. Since AV technologies are still in an early stage of development, innovations in the design of mounting including materials and structures, and the development of best practices could help reduce the land preservation cost in the future. The modeling approach in this study can remain a valuable tool toward better understanding the economic feasibility of AV as the technology develops in future. Although a simple approach is used for modeling crops in the current work, more sophisticated models and field validation can be incorporated for the crop yield changes, water use efficiency, microclimate impact on the module efficiency, changes in the operation and maintenance costs, and soiling impact will be addressed in future work.

**APPENDIX**

**A. Effect of Different Orientations**

Fig. 9 shows the impact of N/S fixed tilt and E/W vertical bifacial orientations on \( Y_{PAR} \) for both high value and low value farm (for \( M_L = 20 \)). There is almost no effect of mentioned orientations on \( Y_{PAR} \) and thus on crops for \( p/h \) greater than 2. For full density \( (p/h = 2) \), there is significant difference in \( Y_{PAR} \) of E/W vertical bifacial and N/S fixed tilt orientations with \( Y_{PAR} \) around 30-40% higher for E/W vertical bifacial orientations. This leads to higher crop yield (and thus revenue) for E/W vertical bifacial orientation but does not translate into higher \( \rho \) for full density \( (p/h = 2) \) as shown in Fig. 9. This is due to the fact that even though more light is available under PV panels for E/W vertical bifacial orientation (thus higher \( Y_{PAR} \)), but energy generated by this orientation is comparatively less than fixed tilt AV system at full density \( (p/h = 2) \), thus resulting in lower \( \rho \) even at lower panel densities for E/W vertical bifacial orientation than N/S fixed tilt orientation.

**B. Effect of Constant Feed-in Tariff**

The electricity tariffs are reducing globally due to continuous improvement in PV technology along with reduction in its costs [38]. In Pakistan, the feed in tariff of PV is also reducing and it is becoming cheaper [39]. In recent years, PV tariff in Pakistan
and thus shifting the trends upwards (in comparison with trends in Fig 2 and 3), thus achieving higher values of \( \rho \) at lower \( \rho/h \) and \( M_L \). Fig. 10(a) shows that the economic equivalence (\( \rho_{th} = k \)) after including \( \Delta FIT \) with respect to GMPV can be obtained for \( N/S \) high value farm for \( M_L = 20 \) at \( \rho/h \) of 6. For the \( N/S \) low value farm [see Fig. 10(a)], however, the economic equivalence is still not approachable implying a much higher \( \Delta FIT \) is required due to low crop income. Similarly, Fig. 10(b) shows that the economic equivalence (\( \rho_{th} = k \)) after including \( \Delta FIT \) with respect to GMPV can be obtained \( E/W \) high value farm for \( M_L = 20 \) at \( \rho/h \) of \( \sim 6 \). For the \( E/W \) low value farm [see Fig. 11(b)], however, the economic equivalence is still not approachable implying a much higher \( \Delta FIT \) is required due to low crop income.

### C. Details on Mathematical Modeling

We will start from (6) in mathematical modeling section, which is given by

\[
\frac{(M_L + \frac{\rho}{h})_{AV}}{(M_L + \frac{\rho}{h})_{PV}} \leq \frac{P_C}{(M_L + \frac{\rho}{h})_{PV}} \times \left( \frac{\chi_0}{\chi} \right) \times A_M + 1
\]

(i)

\[
(M_L + \rho/h)_{AV} \times \frac{1}{Y_{PV}} = (M_L + \rho/h)_{PV} + \frac{P_C}{(C_{L/+\chi}) \times A_M}
\]

(ii)

\[
(M_L + \rho/h)_{AV} = Y_{PV} \times (M_L + \rho/h)_{PV} + \frac{Y_{PV} \times P_C}{(C_{L/+\chi}) \times A_M} - \left( \frac{p}{h_{AV}} - \frac{p'}{h_{PV}} \right)
\]

(iii)

\[
M_{L_{AV}} - M'_{L_{PV}} = \frac{Y_{PV} \times P_C}{(C_{L/+\chi}) \times A_M} - \left( \frac{p}{h_{AV}} - \frac{p'}{h_{PV}} \right)
\]

(iv)

\[\frac{C_{M_{AV}} - C'_{M_{PV}}}{C_L} = \frac{Y_{PV} \times P_C}{(C_{L/+\chi}) \times A_M} - \left( \frac{p}{h_{AV}} - \frac{p'}{h_{PV}} \right)
\]

(v)

\[
\frac{C_{M_{AV}}}{C_{M_{PV}}} = \frac{Y_{PV} \times P_C}{(C_{L/+\chi}) \times A_M} - \left( \frac{p}{h_{AV}} - \frac{p'}{h_{PV}} \right)
\]

(vi)

\[
\frac{C_{M_{AV}}}{C_{M_{PV}}} = \frac{Y_{PV} \times P_C \times \chi \times p/h_{AV}}{C_{M_{PV}}} - \left( \frac{p}{h_{AV}} - \frac{p'}{h_{PV}} \right)
\]

(vii)

\[
\frac{C_{M_{AV}}}{C_{M_{PV}}} = \frac{Y_{PV} \times P_C \times \chi \times p/h_{AV}}{C_{M_{PV}}} - \left( \frac{p}{h_{AV}} - \frac{p'}{h_{PV}} \right)
\]

Knowing that \( \frac{A_{L,PV}}{A_{L,AV}} = \frac{p}{\pi_{PV}} / \left( \frac{p}{\pi_{AV}} \right) \), where \( A_{L,PV} \) is the land area occupied by GMPV and \( A_{L,AV} \) is land area occupied is between 5 to 7 cents per KWh so by increasing it by 50% for \( AV \) in order to meet the additional costs for \( AV \), a hypothetical case is presented depicting the effect of \( FIT \) for \( M_L \). Fig. 10 shows \( \rho \) versus \( \rho/h \) trend in the presence of \( \Delta FIT \) for \( N/S \) and \( E/W \) faced module orientations, respectively, for the two crop rotations. Feed-in Tariff resulted in providing offset
by AV. Using $\alpha = \frac{Y_{PV} \times p/h}{C_{M_{PV}}} \quad \& \quad \kappa = \left( \frac{C_{M_{AV}}}{C_{M_{PV}}} \right)$, we get

\[
\left( \frac{C_{M_{AV}}}{C_{M_{PV}}} \right) = \alpha \times P_C \times \chi - \left( \frac{1}{Y_{PV}} - \frac{A_{L,PV}}{A_{L,AV}} \right) \alpha \cdot c_L + Y_{PV}.
\]

The effect of light homogeneity for the crops is incorporated in the calculation of $Y_{PAR}$, i.e., the relative crop yield as compared to full sun. The spatial-temporal model for photosynthetically active radiation ($PAR$) that we have used in this article is described in detail in our recent paper [23]. The effect of pitch on light homogeneity (normalized $PAR$) is shown for both N/S fixed tilt and E/W vertical bifacial orientations for four different months across the year in Fig. 12 (reproduced from [23]). The figure illustrates that E/W vertical retains $PAR$ homogeneity across all seasons while N/S tilted shows a significantly nonhomogeneous shading underneath the modules. The N/S modules are tilted $20^\circ$ toward south and the bottom edges of the subsequent rows of modules lie at distance ($d$) = 0 and 4 m. For E/W vertical, the subsequent module rows are positioned vertically at $d = 0$ and 4 m.

### D. Crop Revenue Inputs

| Months | Crop     | Revenue ($/ha$) |
|--------|----------|-----------------|
| Apr-Jun| Tomato   | 948.81          |
| Jul-Sep| Cauliflower | 1,145.98       |
| Oct-Mar| Garlic   | 7,097.54        |
| Total  |          | 9,192.34        |

### TABLE I
Cropping Cycle and Net Profit From Tomato, Cauliflower, and Garlic (High Value Farm) for Khanewal

| Months | Crop     | Revenue ($/ha$) |
|--------|----------|-----------------|
| Apr-Sep| Cotton   | 69.88           |
| Oct-Mar| Wheat    | 228.43          |
| Total  |          | 298.31          |

### TABLE II
Cropping Cycle and Net Profit From Cotton and Wheat (Low Value Farm) for Khanewal

### TABLE III
$\Delta FIT$ (in %) required for AV to achieve an economic equivalence with respect to $GMPV$ (HV and LV Farm) for Khanewal

| $M_L$ | p/h | N/S HV | E/W HV | N/S LV | E/W LV |
|-------|-----|--------|--------|--------|--------|
| 10    | 2   | 15.22  | 16.79  | 11.60  | 10.85  |
|       | 3   | 19.10  | 21.33  | 10.13  | 11.36  |
|       | 4   | 23.03  | 25.88  | 10.53  | 11.95  |
| 15    | 2   | 15.22  | 16.36  | 11.60  | 10.43  |
|       | 3   | 17.95  | 19.35  | 8.98   | 9.37   |
|       | 4   | 20.72  | 22.34  | 8.22   | 8.41   |
| 20    | 2   | 15.22  | 16.15  | 11.60  | 10.22  |
|       | 3   | 17.08  | 18.36  | 8.11   | 8.38   |
|       | 4   | 18.99  | 20.57  | 6.49   | 6.64   |
| 30    | 2   | 15.22  | 16.15  | 11.60  | 10.00  |
|       | 3   | 16.41  | 18.36  | 7.44   | 7.39   |
|       | 4   | 17.64  | 20.57  | 5.14   | 4.87   |

### E. Effect of p/h on Light Homogeneity

The effect of light homogeneity for the crops is incorporated in the calculation of $Y_{PAR}$, i.e., the relative crop yield as compared to full sun. The spatial-temporal model for photosynthetically active radiation ($PAR$) that we have used in this article is described in detail in our recent paper [23]. The effect of pitch on light homogeneity (normalized $PAR$) is shown for both N/S fixed tilt and E/W vertical bifacial orientations for four different months across the year in Fig. 12 (reproduced from [23]). The figure illustrates that E/W vertical retains $PAR$ homogeneity across all seasons while N/S tilted shows a significantly nonhomogeneous shading underneath the modules. The N/S modules are tilted $20^\circ$ toward south and the bottom edges of the subsequent rows of modules lie at distance ($d$) = 0 and 4 m. For E/W vertical, the subsequent module rows are positioned vertically at $d = 0$ and 4 m.

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