Optimal Photovoltaic Array Layout of Agrivoltaic Systems Based on Vertical Bifacial Photovoltaic Modules

*Roberta Arena, Stefano Aneli, Antonio Gagliano, and Giuseppe Marco Tina**

An agrivoltaic (APV) plant is a complex system, where photovoltaic (PV) energy generation is concomitant with agricultural production. These activities can be antagonistic as the presence of PV installation might reduce the favorable conditions for agriculture and vice versa. In this context, vertical bifacial PV (AbPV) farms represent a fascinating perspective to optimize the land's dual-use request. This means finding geometrical configurations for the AbPV plant to produce the same energy as ground-mounted PV farms, not hinder agricultural activities, and limit the photosynthetically active radiation deficit. This study evaluates the performances of a vertical bifacial APV plant, located in Sicily, as a function of the PV modules' plan allocation. The analyses developed through two software tools, SAM and PVsyst, compare the relative capabilities of monofacial and vertical bifacial farms in terms of acceptable PAR debit, and energy yield as a function of the array density. The land equivalent ratios of vertical AbPVs from a maximum value of 1.93 ($p/h = 2.5$) and a minimum of 1.56 ($p/h = 5.0$) for crops which have low sensitive response to the drop of solar radiation, while from 1.71 and 1.42 for crops which have higher sensitive response to the drop of solar radiation.

1. Introduction

The implementation of photovoltaic (PV) technology may cause environmental consequences such as land use, thermal and climatic effects, and emissions. In particular, a relevant issue of ground-mounted PV plants is often depicted in land use competition with crop production. In this context, the combination of PVs and plant production, the so-called agri photovoltaic or agrivoltaic (APV) systems, has been suggested as an opportunity for harvesting food and energy jointly.[1] This leads to singular co-optimization challenges for the placing of the PV modules, the height of the modules from the ground, and the support systems as well as in the use of different PV technologies in comparison with the traditional solar farms. Generally, the performances linked to energy production and agricultural activities could be in opposition; a solution that privileges only one of the two components, PV or agriculture, is liable to have adverse effects on the other.[2] Maximizing the energy yield by PVs can create unfavorable conditions for agriculture and vice versa (e.g., shading can have negative consequences on photosynthetic efficiency; the structures of PV can interfere with the use of mechanical means used in agriculture, and so on). An APV system, which consists of PV modules and the empty space between and underneath the modules (APV volume), mounted in structures that support the agricultural function or any other extra purposes, is a complicated system that is both energetic and agronomic.[3] APV farming gives rise to coactive benefits like reduced evapotranspiration,[4] landscape preservation, and socioeconomic well-being of farmers,[5] as well as upgraded agricultural production,[6] ecology, and biodiversity.[7] Moreover, APV plants can contribute to enhancing the resilience of the agricultural sector to the always more frequent heat wave and drought periods, especially in the hottest and arid areas of the planet.[8]

1.1. Crop Yields and Livestock

One of the main focuses for developing the APV systems should evaluate mitigation strategies for contrasting the light reduction and selecting the most suitable varieties of crops. The crop yield may depend on many aspects, such as the sensitivity to the microclimate factors like temporal/spatial variation of solar irradiation, wind velocity, water amounts, and so on. However, the intensity of solar radiation is the most determinant factor for the crops grown within an APV plant.[9] The crop yield can be related to the amount of photosynthetic active radiation (PAR) which is the portion of the light spectrum, between 400 and 700 nanometers wavelength range, utilized by plants for photosynthesis.[10] PAR meters typically measure photosynthetic photon flux density as the number of photons per square meter per second. (μmol m^2 s^{-1}).[11] João F. Escobedo observed that the PAR ratio over the incident global radiation varied from 48.66% (2003) to 50.00% (2004).[12] ENEA, the Italian Center for Renewable Energy, has elaborated monthly maps of PAR on a horizontal surface for a period of 24 h, in the whole Italian territory.[13] The impact of land use intensity, which has a meaningful role in the feasibility of the APV's solution, can be evaluated using

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parameters like the ratio between land area occupied over energy generated (ha kWh^{-1}) and/or land area occupied over installed power capacity (ha kWp^{-1}).[14] Dupraz et al. to determine the advantages achievable from an APV plant with respect to a distinct use of the same plot area for agricultural scope and PV production (PV and farm set up separately), introduced the land equivalent ratio (LER),[15] which allows assessing whether the joint contributions of agricultural yield and energy are equal or lesser than those achievable from a single use of the land. Although full shading from PV panels causes a loss of crop production by 50% to similar crops in the full-sun plot, Wolff et al. observed beneficial effects from shading up to 30%–47%, lettuce showed a 36%, head cabbage, and Chinese cabbage a 23% and 21%, respectively, yield increase.[16] Martínez et al. carried out a qualitative analysis to assess the effects of the presence of PV modules on the bean plant growth and no variation in height and in the appearance was noted analyzing plants grown in full sun and those grown in the area subject to modules shading.[17] In **Montpellier** (43° 65′N, 3°87′ E), the LER increases by 35%–73% for solar arrays arranged with two densities of solar modules: full and half densities, respectively.[18] Majumdar and Pasqualetti modeled the APV system at **Phoenix**, AZ, USA, for half and quarter density of solar arrays (half and a quarter of the agricultural land area is covered with panels respectively, as compared with an open field) and showed that south-faced solar arrays titled at 30° received 60% and 80% of the total global radiation for half and quarter density of solar arrays respectively.[6]

Livestock activities can also coexist along with PV, Andrew, who analyzed the lamb growth and pasture production in Oregon under PV, detected an increase in land productivity of up to 200% as well as a more animal welfare and friendly environment.[19]

Livestock conveys shade preference, animals stayed more than 70% of the time under PV shading when the irradiance was greater than 800 W m^{-2}, as Maia et al. have observed.[20] Several studies and applications have been aimed at optimizing the overall APV systems performance by using different heights, row widths, module tilts, module orientation, and module transparencies to fit different agricultural needs (e.g., provide additional shade for crops which may not tolerate high levels of sunlight).[21]

1.2. Installation Challenges and Potential Solutions

Yussuf et al. have evaluated, through PVsyst, the possibility of creating APV systems in Sweden. The results suggest that the optimal for agricultural production would be obtained with distances between the strings of 10 meters, instead for the electricity production with distances of 5 meters. In these locations it is important to lift the modules from the ground to avoid the decrease of production in the colder months due to the accumulation of snow.[22] The optimum distance can vary greatly depending on the area of interest and the type of crop. Malu et al. calculated that a distance of just 1.8 meters is sufficient to ensure good insolation to the vine in India. They plan to install the structure raised above the ground, with tilt angle optimized through the calculations obtained with the software SAM.[23]

However, elevated mounting structures not only significantly affect the cost of installation and the environmental impact but also have an influence on their social acceptance. The additional costs related to the installation of elevated-mounted PV to 3–5 m, difficulty to clean, and site preparation are assumed to be more than double compared to a ground-mounted PV plant (from 0.3 to 0.7 EUR kWp^{-1}).[24] Vertically tilted APVs give rise to several practical advantages like reduced land coverage, which creates the slimmest interference to the farm equipment and rainfall. Moreover, it is possible to install the PV modules much closer to the ground so decreasing the installation costs and allowing easier access for cleaning, as well as reducing soiling losses.[25,26] In regions characterized by very long drought periods (e.g., Asia, Middle East, North Africa, and South Europe) where power losses due to soiling in tilted modules could be higher than 1% per day,[27,28] vertical APV configurations could be especially advantageous since soiling losses are strongly mitigated as the module tilt varies from horizontal to vertical.[29] A trade-off evaluation between traditional crops for food/feed cultivation on not-watered arable land and energy production was assessed in the work of Sacchelli et al.[30] Muthu et al. carried out an investigation to find the best possible orientation for vertical bifacial PV modules in India, with and without tracking, evaluating various technical, environmental, and economic parameters.[31] Rucker et al. assert that PV modules vertically installed can generate competitive amounts of electricity if designed properly, and in particular they suggest the use of double high modules, by-pass diodes and to decouple the bottom and top modules through two inverters.[32] Johansson et al. found out, through fluid dynamic simulations, that bifacial PV modules, if installed vertically, can achieve greater efficiency than tilted ones, thanks to lower operating temperatures.[33]

1.3. World Progress

Armin Zastrow and Adolf Goetzberger in 1981 were the first to conceive the idea of using the same piece of land for both agricultural and energy production and Akira Nagashima in 2004 developed the first prototype. A greater diffusion of these systems in Japan occurred just in 2012 with the introduction of the feed-in tariff, enacted to incentivize the development of renewable energy after the Fukushima accident.[34] Today, APVs systems are entering the markets in many regions of the world. Jamil et al. calculated that by installing vertical APV on only 1% of the cultivated area in Canada, more than a third of the country's electricity needs could be met.[35] Despite the potential attractions for this kind of APV, there is a lack of knowledge on the potential of vertical bifacial farming AbPV. The Next2Sun company (GE) realized APV in Austria and Germany with vertical bifacial PV modules facing East and West and leaving the areas between the rows (about 10 m) for the cultivation of potatoes, hay, and silage.[36] Insolight, a European company specialized in APV, realized semitransparent PV modules to be installed instead of the conventional plastic structures used to protect the crops.[37] Recently, the "Guidelines on Agricultural PV Plants" has been published in Italy. Such guidelines describe the minimum characteristics and requirements of a PV plant to be defined as APV, as well as for access to the National Recovery and Resilience Plan's (PNRR) financial incentives.[38]

1.4. Numerical Simulation

Although there is a great attraction in the commercial PV market for bifacial solar modules (bPV), their potentiality in APV farms has not yet been studied in insight.[39] One reason is the difficulty in predicting the performance of bifacial PV systems,[40] which also requires modeling the radiation received by the rear side of the PV module. Unless for vertically mounted PV modules, the ground-reflected radiation is significantly greater than the beam and diffuse sky radiation received by the rear side of the PV module. The ground-reflected radiation is also very difficult to determine because it is reduced by a restricted view of the sky, and the shadows from the array.[41] Two different approaches for modeling the radiation on the rear side of the PV module may be defined, the classic view factors and ray-tracing simulation by means of specific software (e.g., Radiance or TracePro).[42] A numerical model for the calculation of shadow lengths as a function of the pitch, the height of the modules, and the incidence angle of the solar irradiation are proposed by Riaz et al.[39] Many studies have evidenced different efficiency of the front/back surfaces of the module under direct and diffuse irradiation as the oblique angle in the diffuse irradiation gives rise to higher reflection loss, thus reducing the conversion efficiency for this component of the solar irradiation.[43,44] As regards the assessment of the rear-side irradiance on bPV module, the numerical analyses carried out with SAM predict approximately 1%–2% less rear-side irradiance than PVsyst.[45] This article addresses these issues by exploring the performances of a vertical AbPV farm placed in the southeast of Sicily, where APV plants could have great potential thanks to the above-aforementioned realistic benefits. Preliminarily, the different performance of the AbPV as a function of their orientation and distance between the arrays (pitch) has been assessed through the software SAM and PVsyst, with the aim of evaluating if there are different results coming from the two software tools considering the peculiarity of the analyzed PV systems. Such analysis could be of interest as there is not great knowledge regarding the numerical simulation of AbPV plants. Subsequently, the energy yield as a function of the pitch between the arrays has been evaluated for the E–W AbPV orientation. One of the unsolved issues is the assessment of the reduction of the solar irradiation that hits the ground, which is a function of the geometry, texture density, and the height of the modules from the ground. Since, currently, there is no direct result from where to derive such information a tailored procedure has been developed for determining the variation of solar irradiation that hits the ground, which allows taking into account the different texture densities of the PV modules. These obtained results could be helpful for scholars in evaluating the amount of sunlight received by the crops and the potential impact on their yield. For each of the different AbPV E–W configurations investigated, the comparative performance of vertically-mounted bifacial solar farms using traditional metrics, i.e., yearly PV energy production and PAR, without considering the complex crop modeling, have been examined for evaluating the coherence with the Italian guideline.

2. Methodology

The analyses presented in this study are carried out using two software SAM and PVsyst.[46,47] The computation of direct and diffuse irradiation hitting the elevated modules is developed using the same procedure followed for ground-mounted PV plants, thereby the numerical models implemented in SAM and PVsyst can be appropriately used. The investigations established by Marion et al. highlighted that the two software provides very similar results.[41] The diffuse and direct components on the PV subarray are calculated through the incident angle algorithm as a function of the position of the sun, the latitude of the place, and the orientation of the modules. The weather data (i.e., solar irradiation, wind velocity, and temperature) can be directly retrieved from the software's database, otherwise can also be provided in input by the user. The main assumptions of the SAM model for bifacial simulation are:[44] bifacial modules are disposed on rows of infinite lengths, this means that no irradiance variation is considered along the same row, and without rear mounting obstructions. As regards the rear-side irradiance on the plane of array (POA), it is weighted by the bifaciality factor (BF), and summed to the front-side irradiance. Then these combined irradiances are converted to DC power using the single-diode model.

$$G = G_{\mathrm{f}} + \mathrm{BF}{*}G_{\mathrm{BS}}(1-\eta_{\mathrm{l}}) \tag{1}$$

where:

G_{f} = POA front-side irradiance
BF = bifaciality factor
G_{BS} = POA backside irradiance
η_{l} = losses

The backside irradiance (G_{BS}) is determined by summing the irradiance received from the sky, the sun, and the circumsolar region of the sky if the angle of incidence on the backside is smaller than 90°, and that one reflected from the ground and the front surface of the PV modules in the row behind.

η_{l} takes into account additional rear-side irradiance losses to approximate:[45]

Mismatch loss between the front and rear sides of the bPV module

Shading due to mounting structures or tracking systems
Soiling on the rear-side of the bPV module

2.1. Performance Metrics

The response of crop yield in APV has been investigated in many field experiments,[15,48,49] as well as modeling studies,[17,50] which envisage different crop yields for an APV farm when compared to an open farm (OF). To assess the performance of an APV system, the LER that leads to comparing the conventional approach (PV and farm set up separately) with the integrated solution on the same land area is usually used.[15] LER measures whether the combined value of agricultural yield and solar energy is equal or higher than it would be from the singular use of land. LER can be computed as:

$$LER = \frac{Y_{\text{Agri-APV}}}{Y_{\text{Agri}}} + \frac{Y_{\text{APV}}}{Y_{\text{PV}}} \tag{2}$$

where:

Y_{agri} = crop yield in a single use of land for farming

$Y_{\text{agri-APV}}$ = crop yield under the APV system for the same area;

Y_{PV} = electricity production under a standard PV system assumption;

Y_{APV} = electricity production for the APV system;

For the purpose to predict the crop yields, it is assumed that the crop yield is primarily affected by the intensity of shade caused by solar modules, and the yield ratio is calculated as a function of g_{grd} using the model proposed by:[51]

$$\frac{Y_{\text{agri-PV}}}{Y_{\text{agri}}} = m \cdot g_{\text{grd}} + (1 - m) \tag{3}$$

where:

the global ground radiation reduction (g_{grd}) incident on the ground for an observed area is calculated as the percentage ratio of the solar irradiation under module coverage to the solar irradiation with no modules installed.[43]

$$g_{\text{grd}} = \frac{1}{k} \sum_{\text{OA}=1}^{k} \frac{H_{\text{OA}}}{H_{\text{global}}} \tag{4}$$

k is varied to cover the entire APV area.

Following this model, the yield ratio has a linear variation, and the slope m is a function of the shade response.

$m \approx 0$ for tolerant response

$m \approx 0.5$ for moderate response

$m \approx 0.75$ for sensitive response

$m \approx 1$ for very-sensitive response

As an alternative, the following nonlinear correlation can be assumed:[52]

$$\frac{Y_{\text{agri-PV}}}{Y_{\text{agri}}} = \alpha_0 + \alpha_1 \cdot g_{\text{grd}} + \alpha_2 \cdot g_{\text{grd}}^2 \tag{5}$$

With $\alpha_0 = -0.095$, $\alpha_1 = 3.64$ and $\alpha_2 = -2.55$

2.2. Performance Ratio

The IEC 71824-1:2021, to assess the performance of a PV plant over time, introduced the array yield (Y_{A}), defined as the ratio between the electrical energy in a defined time interval, E_{el}, and the nominal electrical power, P_{nom}, and the reference yield (Y_{R}), defined as the ratio between the solar radiation energy per surface unit in a defined time interval, H and G_{STC}:

$$Y_{\text{A}} = \frac{E_{\text{el}}}{P_{\text{nom}}} \tag{6}$$

$$Y_{\text{R}} = \frac{H}{G_{\text{STC}}} \tag{7}$$

The array yield (Y_{A}) represents the number of hours during which the electrical power would need to be at nominal power to contribute the same energy production. The reference yield (Y_{R}) represents the number of hours during which the solar radiation would need to be at reference irradiance levels to contribute the same incident solar energy. The performance ratio P_{R} defines the overall solar PV plant performance. It is the ratio of the energy effectively produced with respect to the energy which would be produced if the system was continuously working at its nominal standard test condition (STC):

$$P_{\text{R}} = \frac{Y_{\text{A}}}{Y_{\text{R}}} \tag{8}$$

2.3. Italian Guidelines on Agricultural PV Plants

Recently in Italy, the "Guidelines on Agricultural PV Plants" has been published. Such guidelines describe the minimum characteristics and requirements of a PV plant to be defined as APV, as well as for access to the PNRR financial incentive.[38]

The conditions that an APV must comply with are related to:

The land area occupation ratio (LAOR), which is the ratio between the area of the modules and the area of land that they occupy, must be less than 40%.

The specific electricity production of an APV ($Y_{\text{agri-APV}}$), compared to the specific reference electricity producibility of a standard PV plant (Y_{APV}), both expressed in GWh ha year^{-1}, should not be less than 60% of this last

$$Y_{\text{agri-APV} \geq 0.6}\, Y_{\text{APV}} \tag{9}$$

The adoption of innovative integrated solutions with modules raised off the ground, in such a way that the PV installation do not influence the degree of connection of the area, i.e., the possible passage of animals, with implications on the use of the area for activities related to animal husbandry.

A minimum height of the modules from the ground is introduced:

1.3 meters in the case of zoo technical activity (minimum height to allow the passage of livestock with continuity);

2.1 meters in the case of cultivation (minimum height to allow the use of functional machinery for cultivation)

It is important to evaluate the effect of the installation of APV systems on the environment by monitoring water saving, the continuity of agricultural activity, (i.e., the impact on crops, agricultural productivity for the different types of crops or livestock), the recovery of soil fertility; the microclimate; resilience to climate change.

3. AbPV Plants Configurations

This study aims to evaluate through numerical simulation the performance of solar farms, which utilize bPVs vertically mounted, considering different geometric configurations. The performances and the energy yields of the investigated AbPV configurations have been evaluated through the SAM software utilizing the weather data of Ragusa, a province with a great agricultural vocation located in the southeast part of Sicily (lat. 36.927 e long. 14.725).

The following flowchart illustrates the analyses carried in this study as well as their logic sequence (**Figure 1**).

Figure 2 shows the monthly solar radiation and diffuse/global ratio in Ragusa.

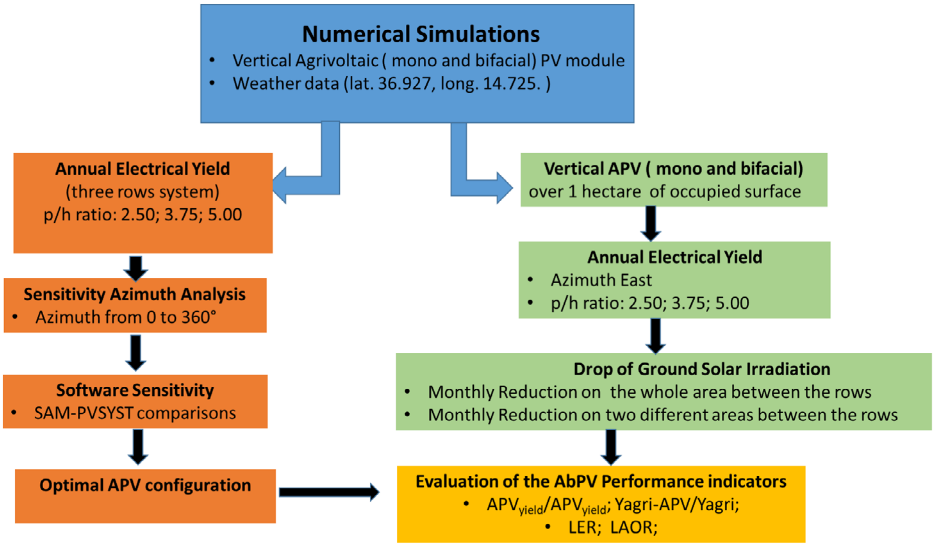

Figure 1. Flowchart of the developed analyses.

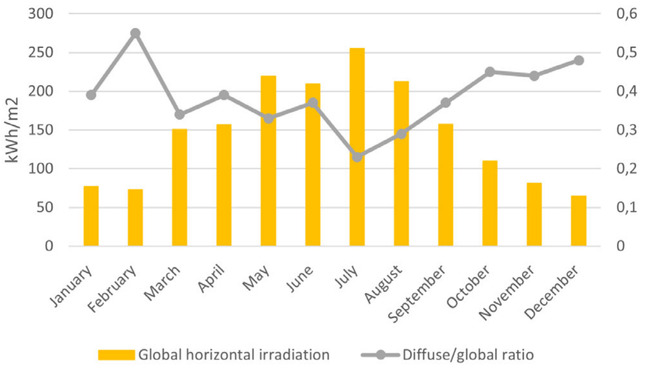

Figure 2. Ragusa's weather data. Data used from Ref. [57].

In the article, the Typical Meteorological Year (TMY) has been used as it is representative of the historical meteorological conditions in given place.

As it is evident that the climate is changing and so probably the future operating conditions of the APVs systems (from the point of view of electrical and agriculture yields). However, the direction of the changes in the different region of the earth is not certain as stated in Ref. [53] for different climate zone in Europe and in Ref. [54], specifically for Italy. In this context it could be useful to use the European Climate Energy Mixes that is a proof-of-concept demonstrator that uses climate and energy data to generate, for a given place, the yearly daily values of the main climate variables for the next years (till 2098) using different Regional Climate Models and emission scenarios.[55] Such input data for APV systems simulations appear affected by a large uncertainties so the use of such data required a specific study that is outside the scope of this research

The energy yield of the AbPV is calculated as a function of the surface azimuth and the distance between two consecutive PV rows, pitch (p), which was varied from 5.0, 7.5, and 10.0 meters. The minimum pitch is set at 5.0 m as it has been evaluated as the minimum distance to ensure the completion of many agricultural activities on the fields. Perez's solar radiation model was used, and the coefficient of albedo considered constant was set to 0.2. Each vertical structure is made of 10 modules that are connected in series, so the whole PV plant is made of 3 strings in parallel, arranged in three arrays. The peak power of the simulated AbPV plant is 10.2 kW. In accordance with the Italian guidelines, the ground clearance height of solar modules from ground was assumed 1.2 m.[38] Therefore, the ratios p/h are about 2.5, 3.75, and 5.0. **Figure 3** shows a sketch of the simulated plant with an E/W orientation.

The features of the bifacial module, used for developing the analyses carried out, are :[56]

Peak power (340/379*W)
Front glass surface (1.983 m^2)
Module length, h (0.998 m)
STC efficiency (17%)
Temperature coefficient ($-0.38\%\ ^{\circ}C^{-1}$)
Bifaciality factor (>85%)

* BSTC = Bifacial standard test condition according with 2Pfg2645/11.17 norm developed for the IEC 60904-1-2 (under final approval)

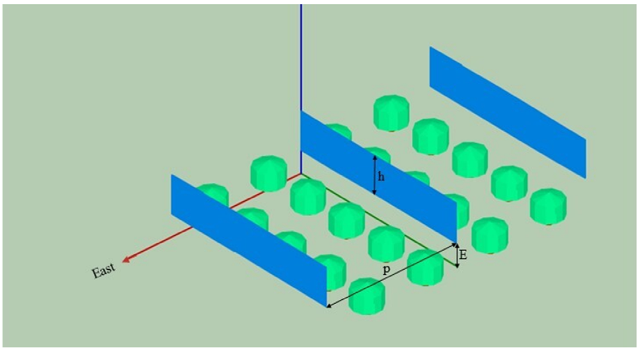

Figure 3. Sketch of the simulated E (90°)/W (270°) oriented PV plant.

4. Numerical Simulations' Results

This section shows the analyses carried out through the software SAM and PVsyst as well as the discussion of the results obtained.

It is noteworthy to underline that it has been assumed that the numerical model, as well as the weather data of the two software are realistic for the evaluation of the shadowing between the PV rows, as well for the prediction of the energy yield for the different configurations investigated.

The main limitations on the presented results are related to neglect the interactions between the crops and the local microclimate that can affect the thermal behavior of the PV modules and consequently to modify their performance.

4.1. Energy Yield as a Function of the Azimuth Orientation and the Ratio p/h

The first analyses carried out to evaluate the AC annual energy yield as a function of the azimuth orientation, the ratio p/h, and a BF equal to 0.85. **Figure 4** shows the variation of the energy yield varying the azimuth orientation from 0 to 360°, with a 10° step, and ratio p/h of 2.5 ($p = 5.0$ m), 3.75 ($p = 7.5$ m), and 5.0 ($p = 10.0$ m). The surface azimuth is referred to the front side of the bifacial PV module.

The analyses carried out allow us to formulate some useful observations:

The electrical production increases as the distance between the rows grows for every orientation of the AbPV plant. This is due to the decrease of the mutual shadow between the PV strings. Such effect is less significant for the S–N orientation ($\gamma_s = 180°$)

The two peaks observed for the azimuths $\gamma s = 100°$ and $\gamma s = 280°$ orientations happen for azimuths 10° more than the East and West orientations. It is interesting to outline that the E–W orientation has an energy yield higher than the W–E orientation. This could be attributed to the specific meteorological data of the investigated site as well as the higher air temperatures reached after midday. Indeed, the solar radiation database PVGIS-SARAH2 indicates that a vertical surface, East oriented, has a yearly in-plane irradiation of 1028.27 kWh m^{-2}, while for the West orientation, the value of 983 kWh m^{-2} is attained.[57]

We can therefore deduce that for vertically installed bifacial modules, the orientation to be preferred, for the maximization of electricity production, should be in the range of 80°–120° or 270°–290°. However, for further analyses, the East ($\gamma s = 90°$) and West ($\gamma s = 270°$) orientation will be evaluated. Moreover, the variation of the energy yield has been investigated as a function of the BF factor.

4.2. Comparison between SAM's Results versus PVsyst's Results

One of the objectives of this study was to compare the electrical production carried out with SAM and PVsyst software. It is worth noting that for both software the diffuse sky irradiance model of Perez, as well as an albedo coefficient of 0.2 were adopted. The analyses were conducted by varying the distance between the strings (5.0, 7.5, and 10.0 m) as well as the BF (0.95, 0.90, 0.85, and 0.65). The software simulates PV systems formed by crystalline silicon modules and assumes that blocking diodes lead to a nonlinear response in the module to partial shadowing. The nonlinear option considers each module equipped with three blocking diodes, and it describes the nonlinear response by applying an empirically determined factor to the electrical output of the subarray. PVsyst gives the possibility to calculate the shading effect with three different models, the one applied to our case is the "unlimited sheds". When the shade first appears, there is a transition that is equal to the width of one cell (half the cell shaded indicates half the current),

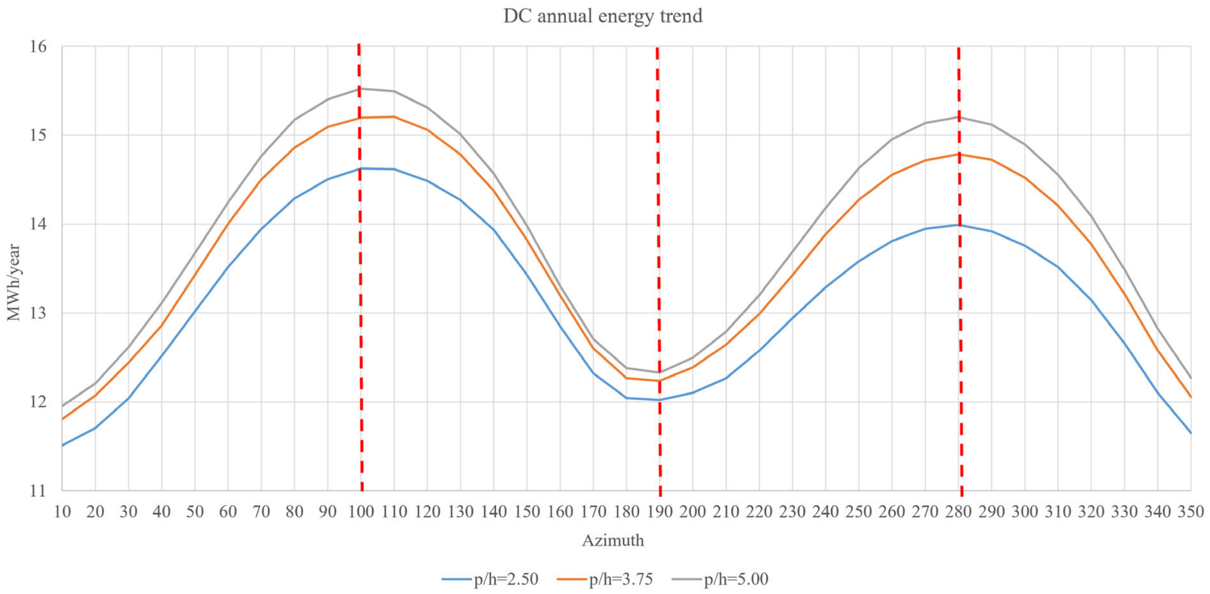

Figure 4. AC annual energy yield as a function of the azimuthal angle of the vertical PV panels.

and then the shading factor is calculated for the string as a function of the profile angle. SAM to take into account the self-shading phenomenon calculates three loss factors, two of them for the reduction of the diffuse POA irradiance and the POA ground reflected diffuse irradiance and the third, which has a direct effect on the DC electrical output, to consider the loss of beam POA irradiance. They are then calculated according to the size of the shadow generated. **Table 1** shows the predictions of the annual energy production carried out by the two software for the two orientations, E–W and W–E, for the above-mentioned plant configurations. The presented results include also a very extreme case, that is BF = 0.65, which could be representative of a loss of performance due to the disuniformity of the solar irradiation on the back side of the bifacial module.

We can notice that in general, the percentage difference between the exposure East and West is derisory, and the results obtained with the two software show a very good agreement. The differences between the predictions obtained with SAM and PVsyst increase with the decrease of the factor of bifaciality, and therefore with the increase of the difference between the production of the front and the backside of the module. In fact, PVsyst provides production data always very similar between East and West, while SAM arrives at differences of 9% for a factor of bifaciality equal to 0.65.

As expected, the energy yield diminishes in coherence with the decrease of the BF factor. It is worth observing that the energy yield diminishes by about 8.85% (p/h = 5.0 m) when the BF decreases from 0.85 to 0.65 for the East orientation, a very similar decrease by 7.82 and 8.04% is observed for p/h = 2.5 and 3.75 m, respectively. The West orientation presents a higher decrement in the energy yield when the BF decreases to 12.54, 13.18, and 13.54% for p/h = 2.5, 3.75, and 5.0 m, respectively. These results are really of interest as they highlight the great importance to guarantee high BF factor for attaining the expected energy yield.

Table 1. Results of software's calculations for the annual energy production with East/West orientation.

	East				West			
	Yearly energy [MWh]				Yearly energy [MWh]			
	SAM	PVsyst	Δ	%	SAM	PVsyst	Δ	%
BF = 0.95								
p/h = 2.5	14.92	15.10	0.19	1.25	14.66	14.99	0.33	2.24
p/h = 3.75	15.54	16.18	0.65	4.16	15.52	16.16	0.65	4.16
p/h = 5	15.93	16.81	0.88	5.52	15.99	16.78	0.79	4.94
BF = 0.90								
p/h = 2.5	14.64	14.73	0.09	0.62	14.23	14.60	0.37	2.60
p/h = 3.75	15.24	15.78	0.54	3.56	15.04	15.74	0.70	4.66
p/h = 5	15.65	16.39	0.74	4.75	15.49	16.35	0.86	5.54
BF = 0.85								
p/h = 2.5	14.36	14.35	−0.00	−0.02	13.80	14.22	0.41	2.99
p/h = 3.75	14.94	15.38	0.44	2.95	14.56	15.32	0.76	5.20
p/h = 5	15.36	15.97	0.61	3.97	14.98	15.91	0.93	6.19
BF = 0.65								
p/h = 2.5	13.23	12.86	−0.37	−2.80	12.07	12.71	0.64	5.30
p/h = 3.75	13.74	13.76	0.02	0.15	12.64	13.65	1.00	7.92
p/h = 5	14.00	14.31	0.31	2.21	12.95	14.18	1.22	9.45

4.3. Energy Yields of AbPV Plant Installed on an Agricultural Field Reference

Once the optimal orientation of the AbPV plant is identified, the analysis is focused on the evaluation of the energy yield as a function of the pitch. A ground area of $10\,000\ \mathrm{m}^2$ is utilized as a reference. The layout of the AbPV plant was designed with PVsyst assuming a regular area (i.e., a rectangle of 125 × 80 m) where the bPV modules are distributed in three sectors. The number of the bPV rows depends on the selected pitch, p, (5.0, 7.5, and 10.0 m), according to the previous analyses. Each row contains 18 modules arranged in two horizontal lines (9 + 9), thus each row has dimensions $L \times h = 18.0\ \mathrm{m} \times 2.0\ \mathrm{m}$. **Table 2** reports the consistency of the AbPV plants as a function of the pitch (i.e., 5.0, 7.5, or 10 m) considering a ground surface of 1 hectare. The peak power is determined considering bPV modules with a peak power of 340 W and a BF of 0.85. The land coverage ratio (LCR) is the ratio of the land area occupied by the mounting structures (area occupied by structure/foundation) to the total land area available at the project site. It quantifies the ground area which is unusable for any other purpose.

As expected, the increase in the pitch implies an enormous reduction of the installed peak power. The installed peak power diminishes by about 30.0% and 45.0% moving from a pitch of 5.0 to 7.5 and 10.0 m, respectively. Such deficits are partially compensated by the increase in energy yield due to the reduction of the shadow between the rows. Thereby, for the above-defined configurations of the AbPV, the yearly energy yield was calculated. For the sake of simplicity, only the E–W orientation of the bPV modules is given in **Table 3**. The latter reports also the energy yields of a vertical APV plant realized with monofacial modules (mPV), which have the same technical feature as the bifacial module (i.e., peak power, electrical efficiency, dimensions, and so on) for the six cases examined, highlighting the loss of production that occurs as the pitch increases.

The column named $\Delta_{(2-1)}$ gives the differences in the yearly production between monofacial and bifacial PV modules. Independently by the distance between the rows, the bifacial PV modules attain an increase in energy production that ranges from 82 to 104%, with the lowest value in December and the highest in May. The increase in energy production higher than 100% could appear surprising, however, it is due to the

Table 2. Configurations of AbPV for distances between the rows of 5.0, 7.5, or 10.0 m.

Pitch, *p* [m]	Number of rows	Number of bPV modules	LCR	Peak power [kW]
5.0	72	1296	0.065	440.64
7.5	51	918	0.046	312.12
10.0	39	702	0.035	238.68

Table 3. Monthly energy yields with p/h = 2.50, 3.75, and 5.00.

	Produced energy [MWh year^{-1}]			
	p/h = 2.50			
	Monofacial (1)	Bifacial (2)	$\Delta_{(2-1)}$	$R_{21} = \Delta_{(2-1)/1}$
Energy yield [MWh year^{-1}]	290.47	556.91	266.44	0.92
Specific energy yield [MWh kW year^{-1}]	0.66	1.26		
PR	0.64	1.23		
	p/h = 3.75			
Energy yield [MWh year^{-1}]	213.38	419.75	206.37	0.97
Specific energy yield [MWh kW year^{-1}]	0.68	1.34		
PR	0.66	1.31		
	p/h = 5.00			
Energy yield [MWh year^{-1}]	173.27	335.69	162.42	0.94
Specific energy yield [MWh kW year^{-1}]	0.73	1.41		
PR	0.71	1.37		

exploitation of the components of the irradiation on the back face of the bifacial PV module (i.e., the irradiance from the sky horizon, reflected from the ground, and from the front surface of the PV modules in the row behind), components that are not effective for the monofacial PV module. These results highlight the great advantage of the AbPV configuration in comparison with conventional AgriPV (AmPV) when the PV modules are installed with a tilt of 90°. The column named $R_{(21)}$ gives the ratio between the additional yearly production provided by the bPV module over the yearly production provided by AmPV. It can be observed that this ratio is almost similar to the BF of the bPV modules. The uppermost yearly energy production is obtained with the bPV plant and for a pitch of 5.0 m, 556.91 MWh y^{-1}, that is, 55.6 kWh m^2 y^{-1}, and the lowermost for the distance of 10.0 m, 335.69 MWh y^{-1}, that is, 33.6 kWh m^2 y^{-1}, with a reduction of the energy yield of 40%. Similar outcomes can be drawn for the monofacial PV plant. As regards the bPV configurations, the energy production diminishes by 137.16 MWh y^{-1} (about 26.5%) and of 221.22 MWh y^{-1} (about 40.3%) moving from a pitch of 5.0 to 7.5 and 10.0 m, respectively. The decrease in the energy production is quite linear, bringing the distance to 10 m the production drops strongly, reaching values lower than 40% for both AbPV and AmPV configurations. It is possible to observe as the AmPV configurations suffer a less reduction of the energy yields in comparison with the AbPV configurations as the more important consequence of the shadow. However, it is worth noting that the specific energy yield, given by the ratio of energy yield/peak power, indicates an opposite behavior. As expected, the highest energy yield is achieved by the AbPV with a pitch of 10 m. Finally, the energy yield of a conventional monofacial PV plant installed on the ground with a tilt angle of 30° and South oriented, has been determined, considering the same peak power of the AbPV configuration with a pitch of 5 m (i.e., 440.64 kW), which gives rise to an energy yield of 543 MWh year^{-1}. The peak power of the conventional monofacial PV plant gives rise to a ratio between the occupied area and the power installed of 2.27 ha MW^{-1}, which is in agreement with the study of NREL which has determined an average ratio of 3.3 ha MW^{-1}.[58] This outcome indicates that a traditional ground-mounted PV plant achieves an energy yield more or less equal to an AbPV plant with a pitch of 5 m having the same installed peak power (i.e., 543 MWh vs 556.91 MWh). The previous analyses allowed to quantify and compare the energy yields of different configurations of vertical AbPV highlighting the consequence of the pitch between rows.

5. Ground Irradiance

As the main advantage of an APV plant is the opportunity to obtain the coproduction of energy and food, it is fundamental to evaluate the interaction of the PV plants with agricultural activities and the effects on crop's growth. It is evident that the increase in pitch facilitates the movements of the agricultural machinery as well as the reduction of the shadow on the ground. So, in this section, the evaluation of the solar irradiation that hits the ground will be evaluated for the different AbPV configurations previously investigated. The evaluation of the drop of the solar irradiation that hits the ground due to the installation of the PV modules is not a simple task. Indeed, the SAM software does not provide this data, but it is possible to obtain the data on solar irradiation on the POA. Thus, the solar irradiation on the ground has been determined considering a horizontal virtual PV plant placed on the ground ($\beta = 0°$), for which the POA can be determined also considering the effect of the shadows determined by the surrounding obstacles. The shadow generated by the vertical AbPV plant has been reproduced through vertical opaque fences placed in the same position as the vertical bifacial modules. Thus, the drop of the solar irradiation is determined as the difference between the unobstructed horizontal solar irradiation and the irradiation that hits the ground surface shaded by the opaque fences. It was assumed an edge of 0.50 m between the vertical fences and the remaining ground, available for the agricultural activities. This means that the useful ground for the crops is reduced of these surfaces.

5.1. Ground Solar Irradiation between the AbPV Rows

The horizontal solar irradiance that hits the ground between the rows without any obstruction, or considering the shadow generated by the AbPV plant was calculated as a function of the pitch. These analyses have been carried out for pitch of 5.0, 10.0 and 15.0 m. The AbPV with the lowest pitch gives rise to the highest reduction of the horizontal solar irradiance, which has an annual drop from 29, 18% and 13% for p/h ratios of 2.5, 5.0, and 7.5. **Figure 5** depicts the drops of solar irradiation which occur during the year on the whole ground area as a function of the pitch ratio.

It is worth observing, for the three configurations, that the uppermost drops of solar irradiation on the ground occur during the summer period when there is the highest availability of solar energy. The configuration with a p/h ratio of 2.5 gives rise to drops of about 30% from May to September and from 30 to

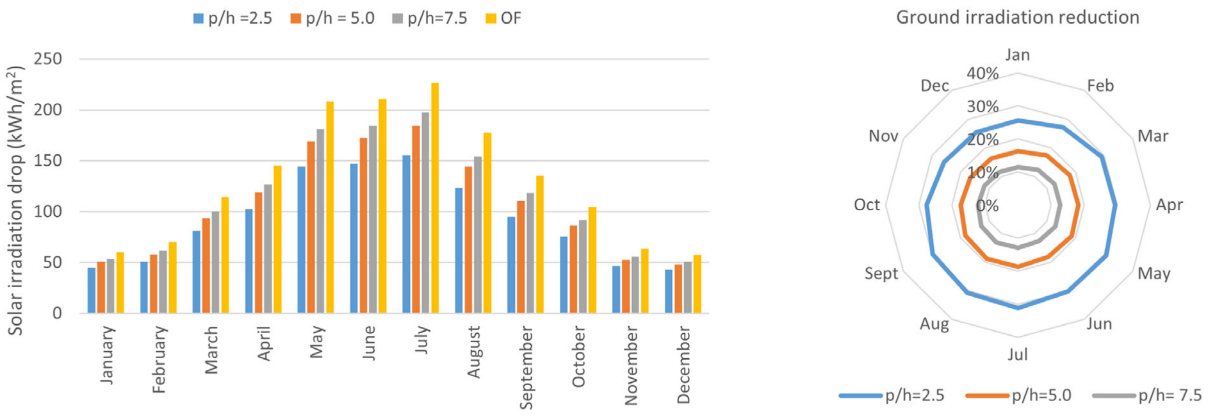

Figure 5. GHI (left) and GHI decreases (right) on the whole ground area for p/h of 2.5, 5.0, and 7.5.

25% for the other months with the minimum drop in December. Similar behavior is observed for p/h ratios of 5.0 and 7.5, for which the decrease in solar radiation ranges from 20 to 15% and from 13 to 11%. Consequently, the less amount of solar irradiation that hits the ground could be neglectable, or even provide positive implications (e.g., decrease in evapotranspiration).[55,59] Moreover, during the first hours of the day in spring/autumn months, the shadow produced by the AbPV E–W oriented is very poor, so the potential risk of frosty morning is mitigated.

5.2. Variation of the Ground Solar Irradiation within the AbPV Rows

This section evaluates the drops of the horizontal solar irradiation (GHI) between the AbPV rows. Two different areas between the rows have been investigated, that are the central strip, (wide $0.4 \cdot \text{p}$), and the two side strips (wide $0.3 \cdot \text{p}$). The procedure followed for determining the drops of solar irradiation is the same as previously illustrated. **Figure 6** depicts the ground irradiation (left side) for the OF in the central and in the side strips for the AbPV, as well as the ground irradiation losses (right side) for pitches of 5.0, 10.0, and 15.0 m (i.e., p/h ratios of 2.5, 5.0, and 7.5).

The results confirm that, for the three configurations, uppermost drops of solar irradiation on the ground occur during the summer period. The side strips record a decrease in solar irradiation higher than the central strip. For the side stripes, the configuration with a pitch of 5.0 m gives rise to drops of about 35% from May to September and from 35.0 to 30.0% for the other months, while lower decreases are observed for the central strip from about 20 to 15%. A similar behavior is observed for the pitches of 10.0 and 15.0 m, for which the decrease of solar irradiation ranges from about 15 to 10% and from 10.0 to 5.0% for the central and side stripes, respectively. These results could be useful for the farmer, who can differentiate the area where different crops may find the microclimate appropriate for their growth.

5.3. Analyses of the Performance Indicator

This section presents the results of the analyses carried out for the calculation of the performance of the investigated vertical AbPV East/West oriented as a function of the pitch between the rows. The Italian guideline for APV systems requires the verification of constraints regarding LAOR as well as the energy yield of the AbPV. The LAOR has been calculated considering that a buffer zone of 0.5 m along each side of the PV rows could be not usable for cultivation. **Table 4** shows the LAOR and the ratio of the energy yield of the AbPV and the conventional monofacial PV plant calculated for the different pitches.

So, it is largely verified the constraint LAOR $< 40\%$. These results indicate that the number of modules can be increased reducing the distance between side-by-side rows. The ratio of the energy yield of the AbPV and a conventional monofacial PV plant is calculated, assuming as reference a PV plant with a tilt angle of 30° and South oriented with the same peak power of the AbPV configuration with a pitch of 5 m (i.e., 440.64 kW), which provides an energy yield of 543 MWh year^{-1}. Since the guidelines prescribe a limit of the energy yield of the AbPV, which has to be at least equal to 60% of the energy yield of a conventional monofacial PV plant, further increase of the pitch does not allow to satisfy this constraint. Finally, the calculation of the LER has been carried out using Equation (2), where the ratio ($Y_{\text{agri-PV}}/Y_{\text{PV}}$) has been calculated through Equation (3), which foresees a linear variation, and the slope m is a function of the shade response. Four different shade responses have been considered, which are: $m \approx 0.25$ for tolerant response; $m \approx 0.5$ for moderate response, $m \approx 0.75$ for sensitive response, and $m \approx 1$ for very-sensitive response. The ratio ($\text{Y}_{\text{APV}}/\ \text{Y}_{\text{PV}}$) has been calculated assuming the yearly yield reported in Table 3 for Y_{APV}, while the yearly yield for a conventional standalone solar PV system was evaluated as 556.90 MWh. The previous energy yields are calculated having as reference an area of 10 000 m^2. **Table 5** shows the ratio ($Y_{\text{agri-PV}}/Y_{\text{PV}}$) and the LER as a function of p/h (2.5, 5.0, and 7.5) and the shade response of the crops.

The most critical condition is associated with the AbPV configuration with a pitch of 5.0 m and crops with the highest sensitive response ($m = 1$), which gives rise to a decrease in the agricultural yield of about 30%. The increase of the pitch, even with the highest sensitive response, gives rise to a decrease in the agricultural yields of about 22% and 18% for $p = 7.5$ and 10.0 m. As $Y_{\text{agri-PV}}$ is strictly associated with the reduction of the ground solar irradiation due to the presence of an APV system, this decrease could be diminished

Figure 6. GHI (left) and GHI decreases (right) for p/h of 2.5, 5.0 and 7.5.

Table 4. LAOR and values energy yield ratio.

p/h	Unavailable space [m^2]	LAOR [%]	AbPV yield [MWh]	AbPV yield /PV yield [%]
2.50	1296	12.96	556.91	100
3.75	918.0	9.18	419.75	75.0
5.00	702.0	7.02	335.69	60.0

excluding the period of the year when there is no cultivation. The LER for all the scenarios investigated is always higher than 1.0. The lowermost performance is associated with the AbPV configuration with a pitch of 10.0 m and crops with the highest sensitive response ($m = 1$), which gives rise to a LER of 1.4, while the better performance is associated with the AbPV configuration with a pitch of 5.0 m and crops with the lowest sensitive response ($m = 0.25$), which gives rise to a LER of about 1.9. It therefore

Table 5. Variation of $Y_{\text{agri-PV}}/Y_{\text{PV}}$ and LER as function of p/h and the shade responses of the crops.

	$Y_{\text{AgribPV}}/Y_{\text{Agri}}$			LER		
	p/h = 2.5	p/h = 3.75	p/h = 5.0	p/h = 2.5	p/h = 3.75	p/h = 5.0
$m = 0.25$	0.93	0.95	0.95	1.93	1.7	1.56
$m = 0.5$	0.85	0.89	0.91	1.85	1.64	1.51
$m = 0.75$	0.78	0.84	0.86	1.78	1.59	1.47
$m = 1.0$	0.71	0.78	0.82	1.71	1.54	1.42

results that the Agri-bPV always achieve higher yield production than the disjointed activities.

6. Conclusion

This work presents a simulation study carried out with the software SAM and PVsyst, which aims to evaluate the potentialities and the limits of an APV plant realized with vertical bifacial modules (AbPV) located in the South–East part of Sicily.

The developed studies have highlighted the following major outcomes.

The first analysis has identified the East/West orientation as the optimal for maximizing the amount of the annual energy yield.

For the East/West orientation, the comparison between a bifacial vertical plant (AbPV) and a conventional monofacial plant that is vertically mounted (AmPV) has indicated that the AbPV plant gives rise to an energy yield of about 2 times higher than the AmPV, whatever is the pitch between the PV rows.

The yearly energy production for an AbPV plant installed on a surface of 1 hectare pitch is of 556.91 MWh y^{-1} for a pitch of 5.0 m, and 335.69 MWh y^{-1} for a pitch of 10.0 m. Although this result could seem trivial, it has to be looked taking into account that the increase of the distance between the rows facilitates the preservation of agricultural activities and also it affects the shading of the soil generated by the PV modules.

As regards, the reduction of the solar irradiation reaching the ground, there are not available tools that allow us to perform this calculation. So, a specific procedure has been developed with the aim to evaluate the decrease of solar irradiation on three different sections of the ground area.

With reference to the whole area between the PV rows

With reference to a section located in the central part of the ground area extended from 0.3 to 0.7 times and the two lateral sections extended 0.3 times of the pitch. The results highlighted that:

Considering the whole area between the PV rows, the solar irradiation decrease is about 30% for a pitch of 5.0 m (p/h = 2.5) and about 12% for a pitch of 15.0 m (p/h = 7.5).

Considering the different sections between the rows, a reduction of 35% was found in the most critical area (close to the PV rows), and of 20% in the central area (in the middle between the PV rows) for a pitch of 5.0 m.

Another interesting outcomes is related to the different reductions of solar irradiation along the months of the year. The highest loss of irradiation occurs in the summer months; thus, at the time of year when the shadowing could be a benefit for the crop's growth. This information could be useful for choosing the crops most adaptable to the microclimate originating within the AbPV plant.

Finally, the requirements imposed by the Italian "Guidelines on Agricultural PV Plants" on the LER were positively verified.

The LER calculations allow to state that the studied Agri-bPVs achieve in the worst case a yield production higher by up to 70% than the disjointed activities. Then from this and other literature studies, we can conclude that through combined energy and crop production, APV can increase land productivity.

The above-mentioned results evidence the great potential of developing the APV technology, and specifically AbPV plant. Moreover, other potential benefits should be taken into account as positive effects deriving from the shading as well as the windbreak effect generated by the APV plant for crop production, which reduces evapotranspiration. Such benefit could be evaluated in terms of the so-called water productivity (ratio of fresh matter to the total actual evapotranspiration). Other advantages of vertical AbPV are also the reduced land coverage, least hindrance to the farm machinery and rainfall, inherent resilience to PV soiling, easier cleaning, and cost advantages due to the potentially reduced elevation.

Further studies will investigate the influence that plants and modules can have on each other, particularly the effect of shading on crops, which in some cases could be positive, and whether the evapotranspiration effect might benefit PV modules by allowing them to operate at lower operating temperatures and thus higher efficiencies. But also discover what kinds of crops might be most suitable, and whether it could be necessary to increase the height of the PV module from the ground for avoiding the shading produced by vegetation in some months of the year.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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agrivoltaic systems, bifacial PV modules, energy generation, land's dual use

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