

Article

Radiation Limits the Yield Potential of Main Crops Under Selected Agrivoltaic Designs—A Case Study of a New Shading Simulation Method

Sabina Thaler ^{1,2,*}, Karl Berger ³ , Josef Eitzinger ¹, Abdollahi Mahnaz ³, Vitore Shala-Mayrhofer ⁴, Shokufeh Zamini ³  and Philipp Weihs ¹ 

¹ Institute of Meteorology and Climatology, BOKU University, 1180 Vienna, Austria; josef.eitzinger@boku.ac.at (J.E.); philipp.weihs@boku.ac.at (P.W.)

² CzechGlobe—Global Change Research Institute CAS, 603 00 Brno, Czech Republic

³ AIT Austrian Institute of Technology GmbH, 1210 Vienna, Austria; karl.berger@ait.ac.at (K.B.); mahnazabdollahi88@gmail.com (A.M.); shokufeh.zamini@ait.ac.at (S.Z.)

⁴ Austrian Chamber of Agriculture, 1015 Vienna, Austria; v.shala-mayrhofer@lk-oe.at

* Correspondence: sabina.thaler@boku.ac.at

Abstract: Agrivoltaics (APVs) represent a growing technology in Europe that enables the co-location of energy and food production in the same field. Photosynthesis requires photosynthetic active radiation, which is reduced by the shadows cast on crops by APV panels. The design of the module rows, material, and field orientation significantly influences the radiation distribution on the ground. In this context, we introduce an innovative approach for the effective simulation of the shading effects of various APV designs. We performed an extensive sensitivity analysis of the photovoltaic (PV) geometry influence on the ground-incident radiation and crop growth of selected cultivars. Simulations (2013–2021) for three representative arable crops in eastern Austria (winter wheat, spring barley, and maize) and seven different APV designs that only limited to the shading effect showed that maize and spring barley experienced the greatest annual above-ground biomass and grain yield reduction (up to 25%), with significant differences between the APV design and the weather conditions. While spring barley had similar decreases within the years, maize was characterized by high variability. Winter wheat had only up to a 10% reduction due to shading and a reduced photosynthetic performance. Cold/humid/cloudy weather during the growing season had more negative yield effects under APVs than dry/hot periods, particularly for summer crops such as maize. The lowest grain yield decline was achieved for all three crops in the APV design in which the modules were oriented to the east at a height of 5 m and mounted on trackers with an inclination of $\pm 50^\circ$. This scenario also resulted in the highest land equivalent ratios (LERs), with values above 1.06. The correct use of a tracker on APV fields is crucial for optimizing agricultural yields and electricity production.

Keywords: hemispherical photographs; digital image processing; HemiView; crop growth model; DSSAT; renewable energy; shadow effect; APV designs; land equivalent ratio



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1. Introduction

In addition to building-integrated PV (BIPV) [1], agrivoltaics (APVs) represent a young and dynamic technological development in Europe that is based on the idea that energy and food production should be co-located on the same land for mutual benefit [2,3]. According to the FAO definition, APV systems are integrated food and energy systems (IEFSs) [4]. Research is focused on co-locating agricultural use and photovoltaic (PV) systems to increase crop yields, reduce the use of resources such as water and pesticides, and produce renewable energy efficiently. One of the most important arguments in favor of introducing APVs into agricultural use is greater resilience in the context of advancing climate

change [5], such as compensating the risk during more intense droughts due to lower evapotranspiration under PV [6]. Climate change has a significant impact on agriculture and water resources, affecting crop yields, water availability, and the overall sustainability of agricultural practices. Fluctuations in temperature, precipitation, and the timing of frost can significantly affect crop growth and yields. For example, higher temperatures and changing precipitation patterns can lead to increased evaporation, reduced water availability, and changes in the timing and distribution of water resources [7]. However, the application of an APV system for crop production must be well thought out and implemented correctly, as it can affect the usual value of the crops produced, especially through shading. In APVs, the crop yield is also reduced by the areas that are no longer under cultivation, such as rows of posts, areas with cables, electrical installations, areas for bracing and anchors, and maintenance paths. On average, they account for approximately 10% of the agriculture area [3,8].

In general, a distinction can be made between two types of plants: shade-tolerant and shade-avoidant plants [9]. Lower light intensities do not impair the efficiency of photosynthesis in shade-tolerant plants. The phytochrome photoreceptors in shade-avoidant plants primarily utilize the shade-avoidance syndrome to improve their light perception (e.g., by lengthening the stem or petiole or changing the leaf angle) [10]. The spectral range (wave band) of solar radiation between 400 and 700 nm that photosynthetic organisms can use for photosynthesis is known as photosynthetically active radiation (PAR), which is primarily reduced by the shadow cast by PV panels on crops [11,12]. The design of the module rows, the APV material, and the orientation in the field have a considerable influence on radiation distribution on the ground [13]. Another important criterion for determining which plant species are suitable for APV systems is the light saturation point. Above a certain point, plants cannot convert additional light into photosynthesis. Plant species with an earlier onset of light saturation are more suitable for APV systems [14]. In addition, the distinction between sun and shade leaves must be considered in APV systems. Leaves that are predominantly exposed to shade are often larger; thus, the little available light reaches a larger area. However, these leaves are usually thinner, as the parenchyma cells with the chloroplasts for chlorophyll formation are mainly arranged next to and not on top of each other. Therefore, the leaf size alone says little about the yields and quality of crops in APV systems. In addition to the size of the leaves, the weight and proportion of secondary plant substances should also be analyzed, which is essential for understanding plant adaptations, ecological competitiveness, and the physiological responses of plants to their light environments. Sun leaves are often smaller and thicker, and their physiological advantage lies in the fact that they evaporate less water despite high solar radiation [15].

As a result, many studies focusing on APVs look at the effect of the heterogeneous radiation conditions on plant growth. In the study by Marrou et al. [16], the hourly temperature profile of the plants influenced by shade during the day (24 h) was analyzed. The ratio between the plant temperature and incident radiation in the morning below the modules was higher. The authors attributed this to the fact that plants lose less sensible heat in the shade (no dew deposition in the morning and reduced transpiration) than in full sun. The average daily temperature of the plants in the shade was not significantly different from that of the control, and the growth rates were similar for all variants. The authors concluded that only minor adjustments to cropping practices are required to move from an open to an APV cropping system and that the focus should be on mitigating light reduction and selecting crops with maximum radiation efficiencies under these fluctuating shade conditions [16]. In the study by Laub et al. [8], most crops showed disproportionately low yield decreases when exposed to reduced solar radiation of up to 15%. There were notable differences in the response curves of some of the crops: a reduction in solar radiation (RSR) of up to 30% was beneficial for berries, fruit, and fruiting vegetables. Other crops such as fodder, leafy vegetables, and tubers/root vegetables had less than proportional yield losses up to an RSR level of 20%, and C3 cereals had less than proportional yield losses up to an RSR level of 15%. Conversely, maize and grain legumes suffered considerable

yield losses even with little shading (from a 1% RSR). Uncertainties in the predicted crop yields depend on the available measurements, response deviations from the RSR, and the observation range [8]. According to the meta-analysis by Asa'a et al. [3] on crop shade tolerance, the best crops right now for APV systems are berries and leafy vegetables grown in semitransparent PV systems.

In addition to light, the temperature and precipitation distributions also have a major influence on plant growth in APV systems. Different distances between the rows of modules and gaps/distances between individual solar modules and the drip edge lead to changes in the precipitation and evaporation distribution on the surface and, in extreme cases, erosion if the water is not channeled away from the drip edge in a controlled manner and water runoff accumulates. Severe soil erosion can occur with inefficient drainage or in the absence of vegetation to absorb runoff water. Moreover, the runoff water can be restricted to smaller areas if the rows are too close together, which can increase the flow velocity and cause erosion [15]. Further changes in the microclimate between APV fields and open fields can be found in the wind speed, dew, evapotranspiration, soil moisture, and temperature.

Due to the increasing number of APV design variants, effective methods for the calculation of the shading effects are needed in order to assess their impact on microclimates and crops. A few studies have been conducted on the connection between APV geometry and incident radiation on the ground. In the study by Jamil et al. [17], vertical PV systems and three different inter-row spacings (5 m, 15 m, and 45 m) were analyzed, and the impacts on crop yields and optimized APV designs were subsequently discussed. The authors used the irradiance model Ladybug Tools plug-in and an interactive 3D graphical user interface (GUI). However, no intercomparison of the simulated data with measurements was carried out. Sarr et al. [18] investigated the influence of higher-mounted PV systems on the incident radiation on the ground as a function of various installation geometries [18]. The authors used a model based on the relationship between the total area occupied by the APV installation and the total shaded area. The shaded area was calculated based on the elevation, the spacing between the panels and that of their rows, the inclination, and the panel size. Model simulations of three scenarios were compared to radiation measurements in the field.

The energy production and rice yield under an APV system were estimated by Kim et al. [19]. The authors calculated the radiation below the APV modules using a machine learning radiation model, which was trained with measured data for one specific APV design. Prakash et al. [20] simulated the radiation and shade distributions over the crop surface among three PV panel densities [20]. The height of the PV systems was kept constant but the inclination was changed using the Autodesk Revit simulation software (Autodesk 2019). Data comparison was also performed.

Our objective was to conduct a sensitivity study on the influence of various APV designs on the ground-incident radiation by considering and intercomparing more types of different PV system geometries. For this, we used a new approach based on the processing of fisheye photographs combined with the globally used and validated radiation/geometry model HemiView [21,22]. Simulations were compared to radiation measurements only for one experimental site with one type of APV design. Validation for each individual scenario did not seem to make sense because the calculation methods were already based on known physical laws and well-known models. Furthermore, it was not feasible and would have been far too expensive. Accurate measurements should not only record the radiation at one point but should also precisely record the distribution of individual meteorological quantities.

We then analyzed the influence of weakened radiation on crop yields within an economic framework using the land equivalent ratio (LER). Here, we assumed that all other yield-affecting microclimatic parameters (e.g., wind, temperature) were not altered compared to open-field conditions, as solar panel shading has the greatest influence on plant growth in APV systems. Moreover, other crop yield-limiting factors that could be indirectly affected by APVs, such as weeds, fertilization, pests, and diseases, were not

considered. The aim of our use case was to identify preliminary optimal combinations of the selected APV systems with relevant crop types with respect to varying annual weather conditions to maximize crop yields and energy production for the drought-prone region of north-eastern Austria.

2. Materials and Methods

2.1. Study Area and Site Conditions

For a hypothetical sensitivity analysis of microclimatic effect on crops, we used weather data from the Hohe Warte climate station in Vienna, Austria ($48^{\circ}15'7''$ N, $16^{\circ}21'24''$ E), which is located 198 m above the sea level in the north of Vienna and is the main station of the Austrian Meteorological Service. This station was selected due to its high-quality measurement data and the fact that it provides both direct and diffuse radiation.

Vienna has the typical continental climate of temperate zones, with little precipitation and snow, lots of cloud cover, mildly cold winter days, and sunny, hot summers. The long-term climate averages for 1991–2020 show a mean temperature of 11.5°C and an annual precipitation of 623 mm. The sunshine duration amounts to 2041.8 h [23]. In this study, daily weather data (temperature, precipitation, and solar radiation) from the years 2013–2021 (9 years) were used.

Winter wheat, spring barley, and maize were selected for this study to analyze different seasonal crops. The temperature and precipitation during the growing season (sowing until maturity/harvest) for each investigated year are summarized in Figure 1. For spring barley, the period runs from March to June, for maize, it runs from April to October, and for winter wheat, it runs from October to July.

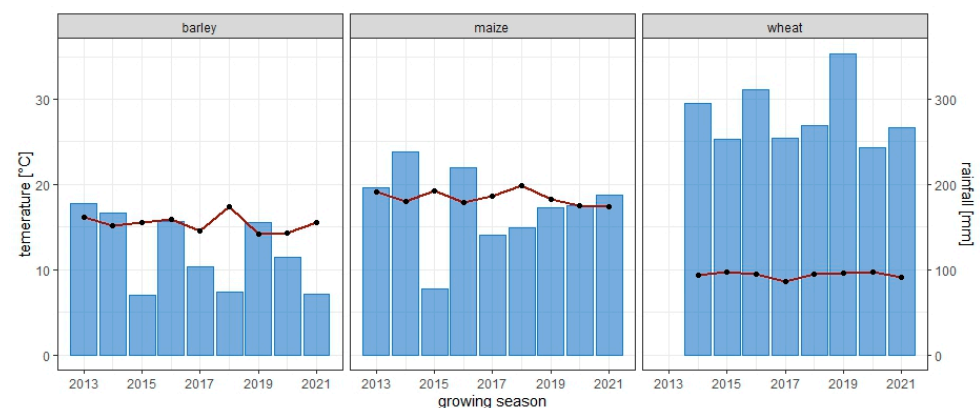


Figure 1. Mean temperature [$^{\circ}\text{C}$] (red lines with black dots = monthly averages) and precipitation [mm] (blue bars) of the Hohe Warte weather station, Vienna, Austria, for the growing periods of spring barley (March–June), maize (April–October), and winter wheat (October–July) from 2013 to 2021.

We selected the chernozem soil type, which presents medium- to high-quality arable land and is typical in northeast Austria.

The model simulations for shading were compared with the radiation measurements on an APV field, which is situated east of Vienna, near Raasdorf, Austria ($48^{\circ}14'40''$ N, $16^{\circ}31'21''$ E). The distance from the Hohe Warte meteorologic station, the data of which were used for the simulation, is 15 km. The APV field consisted of vertical PV rows with a height of 2.80 m, a distance between the rows of 10 m, and a PV row length of 50 m. The photosynthetic active radiation (PAR) measurements were carried out perpendicular to the PV rows. A transect of 10 radiation sensors was set up at a height of 80 cm. Continuous measurements at a 10 min interval were carried out, starting from the 17 April 2024.

2.2. Simulation of Radiation Below APV Modules

As mentioned above, we focused on the effects of the changes in the incident solar radiation on the ground related to the shading and obstruction of the horizon by the APV modules. Figure 2 shows the calculation process for the influence of APVs on the incident solar radiation on the ground. At the beginning, as already mentioned above, the location and time period of the simulations needed to be defined. Then, meteorological data on the air temperature, wind, and precipitation and high-quality direct and diffuse solar radiation ARAD data [24] for the entire 9-year period were downloaded. These radiation data included the incident irradiance on a horizontal plane. Afterwards, the geometry (height, length, width, and inclination) of the APV modules was defined in different scenarios (Figure 3a–f and Table 1).

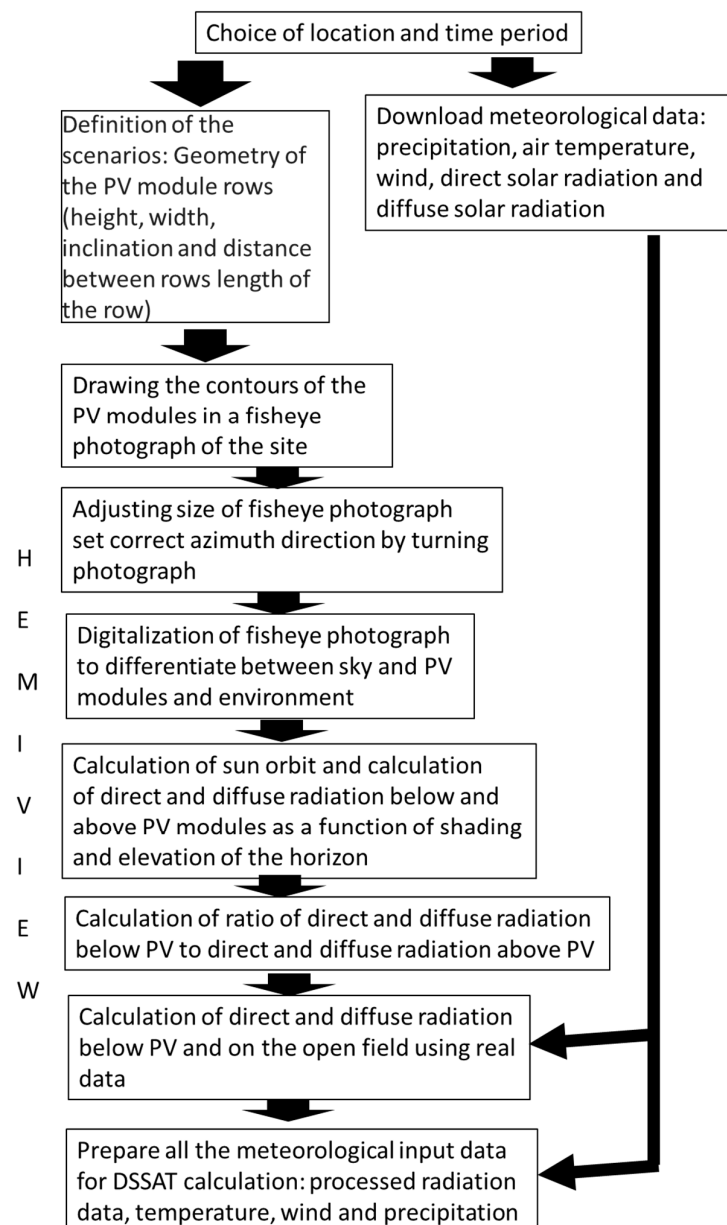


Figure 2. Overview of the calculation process for determining the influence of PV on incident solar radiation and the preparation of the meteorological input data for the DSSAT simulations.

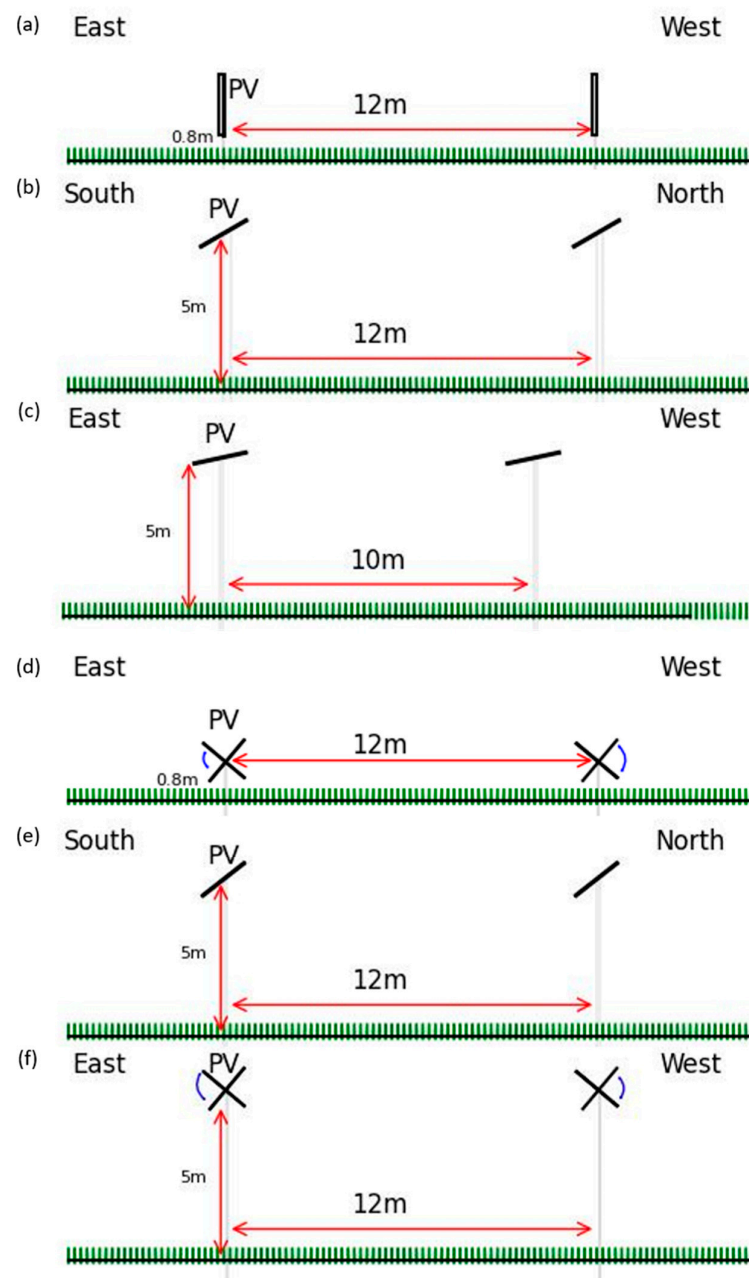


Figure 3. (a–f). The V01–V07 scenarios. PV: PV modules. The height above the ground and the distance between the rows are indicated. Please note that (b) describes scenarios V02 and V05, which only differ in the length of their rows (V02 11.98 m and V05 147.7 m, respectively). (a) In scenario V01, the PV modules are assumed to be in the vertical position with a lowest height above the ground of 0.8. (b) Scenarios V02 and V05 have different row lengths. The PV modules are at a 5 m height with 30-degree inclination, facing south. (c) Scenario V03 has PV modules with 12-degree inclination at a 5 m height and facing east. (d) Scenario V04 has a tracker mounted at a 1.3 m height with a minimum height between the PV modules and ground of 0.8 m. The PV modules are aligned north–south, so they are facing the eastern or western direction and their inclination changes within ± 50 degrees. (e) The V06 scenario is similar to V05 but with a module inclination of 38 degrees. (f) V07 is similar to V04, but the PV modules are at a 5 m height. Blue lines show in which direction the PV module can move. Black lines show the PV modules.

Table 1. Different APV scenarios and their characteristics.

Scenario	Distance Between Rows [m]	Lowest Height [m]	Distance Between Frames [m]	Dimension Modules [mm]	Bifacial [yes/no]	Inclination [°]	Orientation [°]	Energy Yield [kWh/kWp/a]	Row Length [m]	Transparency [%]	Tracker [yes/no]
V01	12	0.8	11.99	1992 × 996 × 30	yes	90°	E-W	1136.8	11.98	0	no
V02	12	5	9.06	1693 × 993 × 4.5	no	30°	S	1201.7	11.98	19	no
V03	10	5	6.68	1683 × 993 × 4.5	no	12°	E	1025.8	11.98	19	no
V04	12	0.8	9	1992 × 996 × 30	no	±50°	E-W	1290.0	147.7	19	yes
V05	12	5	9.06	1992 × 996 × 30	no	30°	S	1201.7	147.7	19	no
V06	12	5	9.06	1992 × 996 × 30	no	38°	S	1201.7	147.7	19	no
V07	12	5	9.06	1992 × 996 × 30	no	±50°	E-W	1253.0	11.98	19	yes

2.2.1. APV Designs Applied for Simulations

The different scenarios selected for the simulations are presented in Table 1 and Figure 3a–f. Scenario V01 is shown in Figure 3a and assumes vertical modules with a bifacial east–west orientation. The module row length is 11.98 m, 80 cm above the ground up to 2 m high, with no module transparency. The distance between the APV module rows is 12 m, which means that the standard machinery size can be used for crop management in the agricultural strips. Scenarios V02, V03, V05, V06, and V07 assume APV modules 5 m above the ground. In scenario V04, shown in Figure 3d, the APV is mounted on a tracker with the lowest APV height at 0.8 m.

More details are given in Table 1, which presents the names of the scenarios (V01–V07), the distances between the rows, the lowest heights of the APV modules, and the distances between the frames, which depend on the row spacing, the module dimensions and inclination. Altogether, an APV system with 10 rows is assumed. Column 6 of Table 1 indicates whether the APV modules are bifacial or not. Column 7 shows the tilts of the modules, which ranged from vertical to 12 degrees, except for the tracker-mounted APV modules (V04 and V07, mentioned in Column 12). The alignment (orientation) of the APV array is given in Column 8. South-facing APV modules are the case with V02, V05, and V06. The lengths of the APV rows are mentioned in Column 10 and are between 11.98 m (V01, V02, V03, and V07: short APV rows) and 147.7 m (V04, V05, and V06: long APV rows); here, a real location with a large APV system is assumed. Moreover, the transparency of the PV panel material (Column 11) is considered, which is assumed to be 19%, whereas a transparency of 0% is assumed only for the bifacial APV. In the following sections, we refer to these V01 to V07 scenarios and compare them with scenario V00, without APVs. We calculated the conditions for the open field, which had no obstructions to the horizon, and maximum incident solar radiation (no shading from APVs), but the same other meteorological conditions as below were calculated for the APV modules.

In addition, energy production was also calculated using the software PV-GIS (for rough estimations) [25,26] and PV*Sol (for detailed estimations) [27] (see Table 1, Column 9). The PV-GIS Tool is a GIS (geographic information system) application for PV systems that offers an easy-to-use application to calculate the irradiation and monthly and annual potential energy production [kWh] of a PV system with a defined size, module inclination, and orientation. PV*Sol (premium 2022) is a dynamic simulation program with 3D visualization

and stricter shading analysis for the calculation of PV systems. The software includes dynamic simulation, design, yield, and profitability forecasts of PV systems, and the 3D menu navigation is divided into six areas: terrain view, object view, module assignment, module assembly, module connection, and cable plan [27]. In the tool, remote shading is calculated via the horizon at the location. However, PV-GIS and PV*Sol do not calculate the ground-incident radiation below the APV system.

2.2.2. Radiation Simulation Methods

Because the main goal of the present study was to quantify the influence of different APV geometries on the ground-incident radiation, a precise and relatively complex calculation approach was chosen (Figure 2). We drew the shapes of the APV modules in a fisheye photo (Figure 4) using the equations below. First, the observer's sight angle (V_{sza}) of the APV module needed to be calculated. Here, the zenith of the sight angle as a function of the azimuth of the view direction is calculated (see Figure 5):

$$V_{sza} = 90 - \arctan \frac{H_{PV}}{dist_{PV}} \quad (1)$$

where V_{sza} is the zenith angle of the sight direction; H_{PV} is the height of the PV modules; and $dist_{PV}$ is the distance of the PV modules.

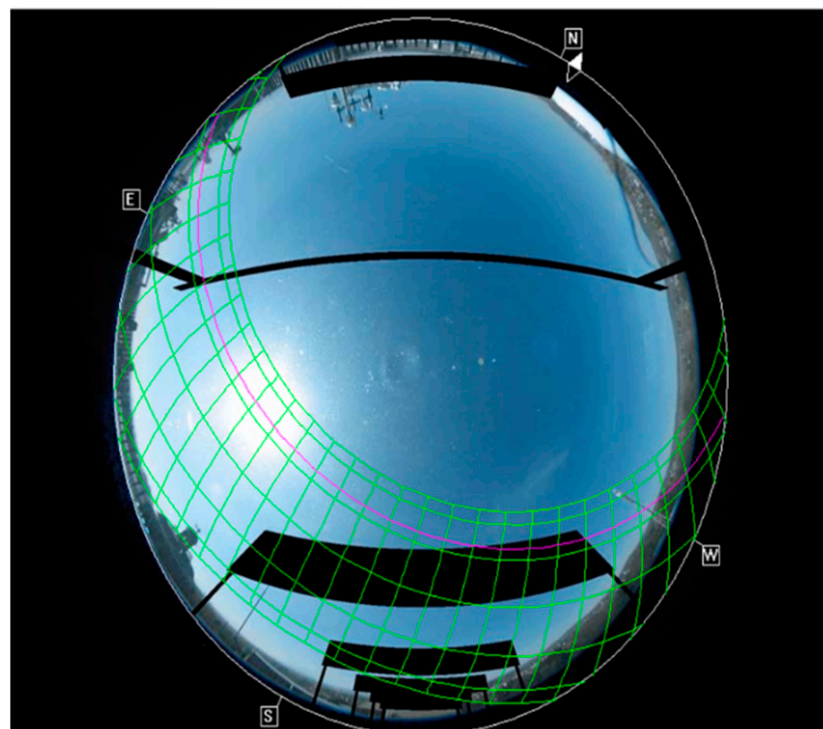


Figure 4. Example of an edited fisheye photograph showing rows of APV modules (scenario V02) with the observer at a 3.09 m distance from the northern APV row and a 5.96 m distance from the southern APV row. The image was processed using the HemiView software, version 2.1 which drew the sun orbit of the individual months and the actual day (purple line) into the image. Circular yellow lines are lines with the same zenith angle, straight yellow lines are lines with the same azimuth angle.

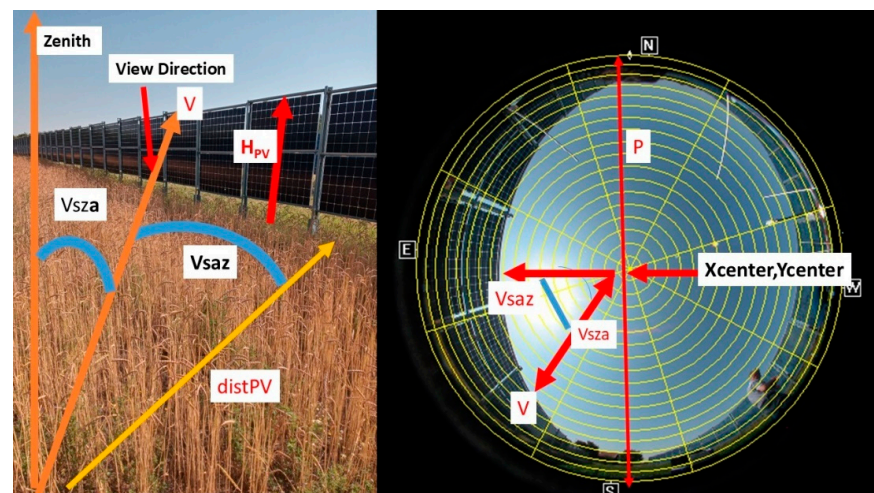


Figure 5. Photograph of the PV system installed at Raasdorf. The picture on the right shows a fisheye photograph. The different symbols used in the equations are depicted. V is the point of vision. P is the part of the image for which the number of vertical pixels (N_y) is specified. Circular yellow lines are lines with same zenith angle and straight yellow lines are lines with same azimuth angle.

The distance between the calculation point and the PV module ($dist_{PV}$) is a function of the calculation point/observer position and the azimuth of the sight direction (V_{saz}) (the direction of the solid angle for which we determine whether a PV module obstructs the sky or not). This distance depends on the minimum distance between the observer (the point of calculation) and the PV module divided by the cosine of the difference between the azimuth at the minimum distance and the respective azimuth angle of the viewing direction. The calculation (the point of calculation is moved) is performed every meter, moving between two rows and perpendicular to the rows. Using the observer/point of the calculation position, we determine the zenith (V_{sza}) and azimuth (V_{saz}) of the viewing angle of a potential observer looking at an APV row. The calculation is repeated for each PV row visible to the observer (visible from the point of calculation), one after the other. When all the sight angles where APV modules are visible are determined, this information needs to be translated into the x and y pixels of a fisheye photograph. The following equations are used here (see also Figure 5):

$$x = x_{center} + \frac{N_y}{2} \times \frac{V_{sza}}{90} \times \sin(V_{saz}) \quad (2)$$

$$y = y_{center} + \frac{N_y}{2} \times \frac{V_{sza}}{90} \times \cos(V_{saz}) \quad (3)$$

where x_{center} is the central pixel of the fisheye photograph of the x coordinate; y_{center} is the central pixel of the y coordinate; N_y is the number of vertical pixels (y direction); V_{sza} is the zenith angle of the sight direction; and V_{saz} is the azimuth of the viewing angle.

For our sensitivity study, it made no difference which background fisheye photo was taken as long as there was no horizon restriction.

Using these processed images, several quantities, such as the diurnal reduction in direct and diffuse solar radiation, were calculated for the 15th day of each month with a time resolution of 30 min using the simulated fisheye photograph and the HemiView Canopy Analysis 2.1 SR5 software (Delta-T devices, www.delta-t.co.uk, accessed on 22 October 2024). This software creates a digitalization of the photograph that allows for differentiation between the blue sky and the horizon, as well as APV modules. Each segment of the sky hemisphere is classified as blue sky or other obstacles. At this point, the sun orbit is calculated for each month. The software then calculates whether the sun is covered by some obstacles or not at each time and day. Using an empirical radiation model, it calculates the incident solar radiation above and below the canopy (APV mod-

ules). From this, a transmission function may easily be calculated for the direct beam for each time interval and day. The obstruction of the horizon (visible sky) is also one of the calculation results. Using the visible sky ratio, it is possible to determine the ratio of the diffuse incident radiation below the APV modules to that above the APV modules. Using the ARAD data of diffused and direct incident radiation on a horizontal plane, we can then calculate the incident irradiance on a horizontal plane below the APV modules using the following equation:

$$Glob_b = Dir \times (r_{Dir} + T) + Diff \times r_{Diff} \quad (4)$$

where $Glob_b$ is the global radiation below the APV modules; Dir is the direct horizontal radiation above the APV modules (taken from ARAD data); T is the transparency of the APV modules (see Table 1); r_{Dir} is the ratio of the direct irradiance below the APV modules to that above the APV modules obtained from the HemiView software version 2.1. calculations; $Diff$ is the diffuse radiation above the APV modules (taken from ARAD data); and r_{Diff} is the ratio of the diffuse irradiance below the panels to that above the panels obtained from the HemiView software calculations.

The resulting global irradiances below (red line) and above (blue line) the APV modules are shown as an example in Figure 6 for the period from 2 May 2020 until 7 May 2020.

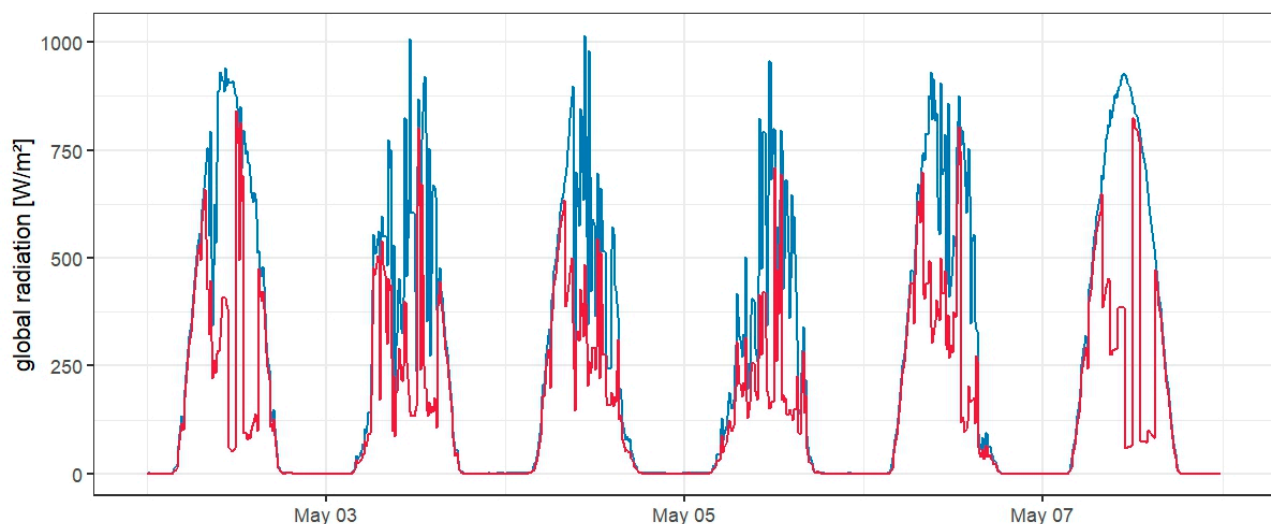


Figure 6. Calculated hourly global radiation data for scenario V02 for the period 2–7 May 2020. The blue line displays the original global radiation data of the ARAD network for Vienna, and the red line depicts the incident solar radiation below the APV modules for scenario V02.

2.2.3. Comparison of Radiation Simulations with Measurements

First, a comparison of the simulated fisheye image was made with a real one taken in Raasdorf (Figure 7). Here, only one scenario (similar to V01) with a distance between rows of 10 m was available for the comparison with the fisheye and radiation simulations. A grid with the zenith and azimuth angles was placed on top to ensure comparability. The angle deviations were in the range of a maximum of 5 degrees, and this was mainly due to the fisheye camera not being optimally leveled during the recordings. The background image was randomly selected and was not considered in the subsequent calculations with HemiView; therefore, it played no role.

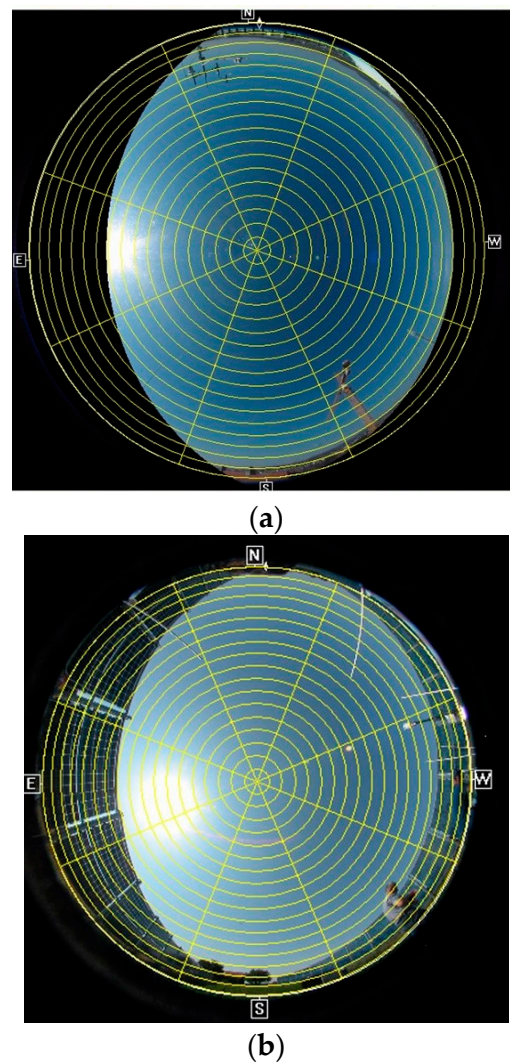


Figure 7. Comparison of (a) edited fisheye photograph and (b) real fisheye photograph taken in Raasdorf. (b) The fisheye photograph was taken at a distance of 3 m west of the PV modules. The background fisheye photograph of the edited photograph was taken from a cloud-monitoring camera situated in BOKU, Vienna, on April 5th. However, the information in the background photograph was not used during the subsequent digitization with the HemiView software. A grid with the zenith and azimuth angles was placed on the images to ensure comparability.

Figures 8 and 9 show the comparison of the simulated and measured radiation below the APV in Raasdorf on a perfect clear-sky day. The PAR was multiplied by a factor of 0.5, following Tsubo and Walker [28]. However, one has to bear in mind that the conversion factor from PAR to global radiation changes as a function of the spectral distribution of the solar spectrum and may fluctuate between 0.43 and 0.5. Figure 8a depicts the diurnal cycle of the global radiation above and below the APV on 27 April 2024. The calculation and measurement point is situated 1 m west of the panels, and the shadows cast in the morning until 9 a.m. are visible. Figure 8b shows the same values as those in Figure 8a but at a distance of 5 m west of the panels.

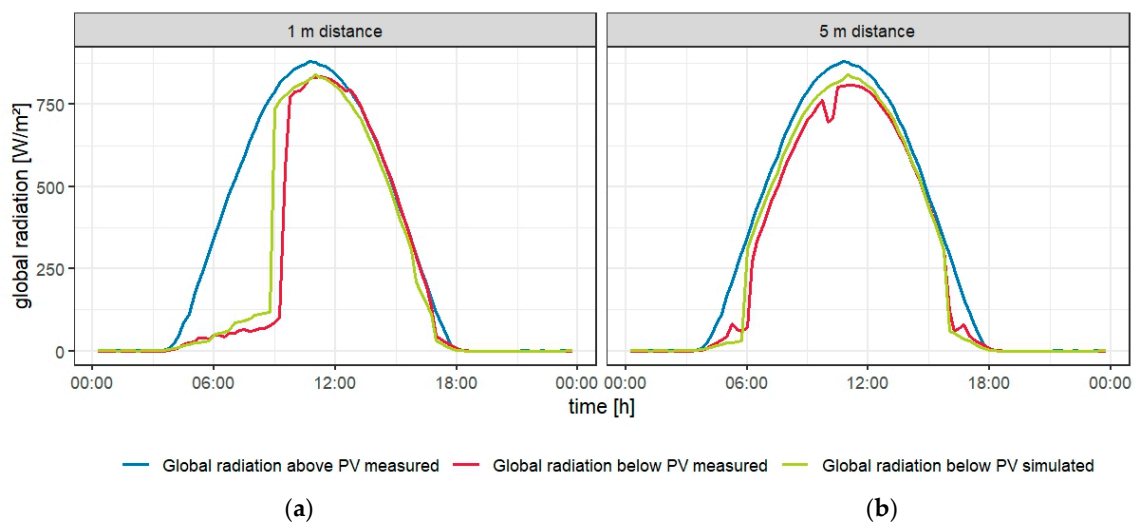


Figure 8. Comparison of simulated and measured radiation on the PV field with the vertical panels. The daily cycle of 27 April 2024 is shown. (a) Radiation at a distance of 1 m west of the panels. (b) Radiation at a distance of 5 m west of the panels. The measured global radiation above the PV system is also displayed to visualize attenuation.

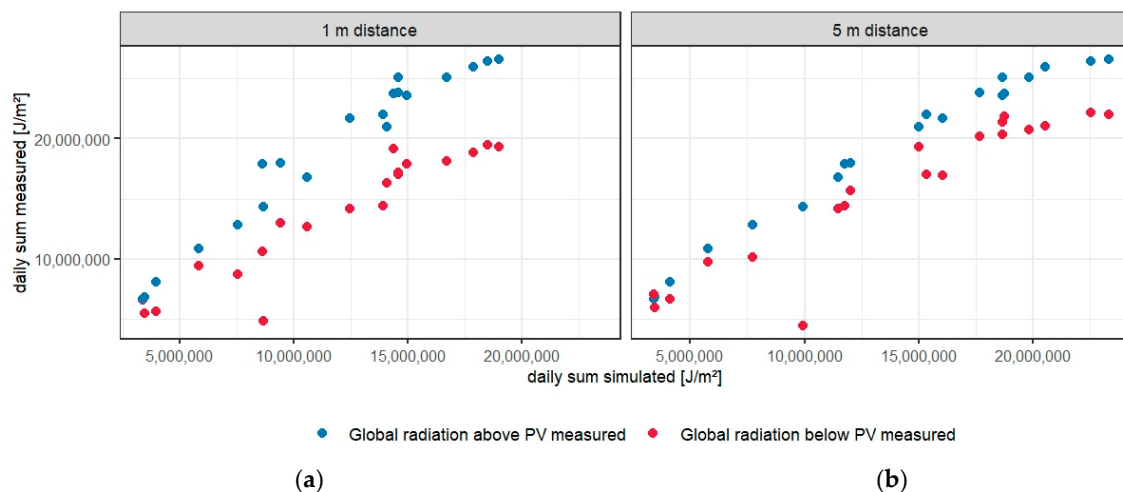


Figure 9. Comparison of simulated and measured daily sums of radiation from 17 April to 8 May 2024. (a) Radiation sums at a distance of 1 m west of the panels. (b) Radiation sums at a distance of 5 m west of the panels. The measured global radiation above the PV system is also displayed to visualize attenuation.

Figure 9a,b present the comparison of the simulated and measured daily radiation sums from 17 April to 8 May 2024. Figure 9a,b show the radiation sums at distances of 1 m and 5 m west of the panels, respectively. Because a multiplication factor was applied to the PAR, only a statement about the accuracy of the simulations in a range of $\pm 5\%$ can be made, demonstrating the correct traceability of the simulated values.

2.2.4. Uncertainty Estimation

As we already mentioned, the radiation calculation was based on mostly accurate radiation data, the processing of fisheye photographs using well-known and accepted optical equations, and calculations using the worldwide-used and -approved model HemiView.

In general, there are three possible uncertainties regarding the radiation calculations:

- Uncertainty about the incoming irradiance above the PV modules, especially related to the diffuse direct ratio: In this study, we used high-quality radiation measurements

comparable to the quality of BSRN stations (highest possible quality), which means that the diffuse direct ratio of the incoming irradiance is mostly accurate.

- Uncertainty about the nonisotropic distribution of diffuse irradiance: Most of the nonisotropic radiation is situated around the sun and is reported as circumsolar radiation [29,30]. Here, a maximum circumsolar irradiance of 10% of the incident direct irradiance normal to the beam may be expected. If the cosine of the solar zenith angle is taken into account, this leads to uncertainties of around 5% and to slightly higher irradiance if the circumsolar radiation is not hidden behind solar panels, whereas it leads to lower irradiance if all the circumsolar radiation is hidden behind the PV modules. Because the sun moves during the day, the positive and negative effects can be expected to balance each other out.
- Multiple reflections may occur between the ground and the PV modules and lead to an increase in the ground-incident radiation. The albedos of soils, crops, and PV modules do not exceed 20%, which may result in an underestimation of the incident ground irradiance of 4% (equal to 0.2×0.2) after two reflections.

2.3. DSSAT Crop Growth Model

The crop model approach was applied to compare the simulated yields of maize, spring barley, and winter wheat under the different APV designs, focusing only on the impact of radiation on crop growth. Here, crop yields below the APV were compared with open-field conditions. The three crops that were chosen for the present study have very different growing seasons, which may influence the response to shading under the different APV designs.

Dynamic crop growth simulation models covering more than 42 crops are part of the Decision Support System for Agrotechnology Transfer (DSSAT 4.8.2) software application program, which is intended to replicate crop growth, development, and yields based on the dynamics of soil water, plants, and the atmosphere. To ascertain a cultivar's growth and phenological development in relation to the photoperiod, thermal time, and dry matter distribution, crop-specific genetic coefficients are necessary [31–33]; to run crop models and assess their results, a dataset is needed as the input, as illustrated in Figure 10.

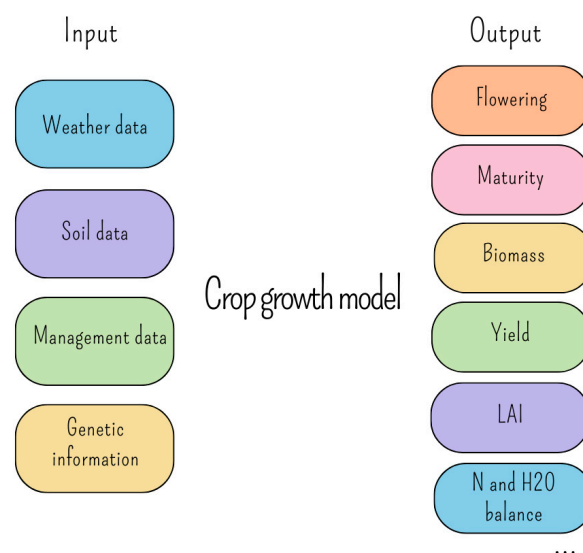


Figure 10. Input and output data of the DSSAT crop growth model.

Daily weather input data were taken from the Hohe Warte weather station in Vienna for the study period and included minimum and maximum temperature (measured) and precipitation (measured) values and direct and diffuse solar radiation. The calculated solar radiation below the APV was added to the input data. Chernozem was chosen as the soil type, which is typical in eastern Austria (approx. 60%) and can be classified as a medium-

to high-quality arable soil. The soil water properties of the selected soil are summarized in Table 2.

Table 2. The soil water characteristics of chernozem soil (up to 1 m soil depth) in m^3/m^3 .

Depth (cm)	LL	DUL	SAT
5	0.185	0.376	0.634
10	0.195	0.396	0.606
25	0.195	0.396	0.606
40	0.206	0.406	0.488
70	0.206	0.379	0.45
100	0.206	0.379	0.45

LL: lower limit of plant-extractable soil water; DUL: drained upper limit; and SAT: saturated soil water content.

For data management, fertilization was fixed (grain maize: $1 \times 80 \text{ kg N/ha}$ and $1 \times 55 \text{ kg P/ha}$, $1 \times 39 \text{ kg P/ha}$, and $1 \times 166 \text{ kg K/ha}$; spring barley: $1 \times 20 \text{ kg N/ha}$, $1 \times 26 \text{ kg P/ha}$, and $1 \times 116 \text{ kg K/ha}$; and winter wheat: $2 \times 50 \text{ kg N/ha}$, $1 \times 26 \text{ kg P/ha}$, and $1 \times 115 \text{ kg K/ha}$), and the sowing dates were selected using the software option “sown under optimum sowing conditions (time window with soil temperature and soil moisture range)”. All three crops were simulated in rainfed mode.

Three different crops were selected as genetic data, which had already been calibrated and validated for the DSSAT model for eastern Austria to ensure that the simulation results reflected realistic trends: winter wheat cultivar, “Capo” [34]; spring barley cultivar, “Magda” [35]; and maize cultivar, “Parzival” [36].

2.4. Data Preparation for Crop Modeling

The simulations of the selected crops were carried out from 2013 to 2021 using the process-oriented growth and yield model DSSAT 4.8.2 for eight variants: the open-field and seven different APV designs (Table 1). For the open-field design, the weather data from the Hohe Warte station, Vienna, were used as the input for the crop growth model; for the different APV variants, the changed irradiation under the APV designs was adopted, while the other weather data remained unchanged.

2.5. Potential for Increased Land Use with APV Systems

APV systems have the potential to outperform separate production systems in terms of land use efficiency. The land equivalent ratio was developed by Mead and Willey [37] to measure the land use efficiency of intercropping systems and is widely used in aquaponics, agroforestry, and, more recently, APVs [3,14,38].

The *LER* is the relative land area needed for mono-production to attain the yields of dual land use. Following Willey [39], the *LER* is specified as the sum of the respective yield ratios of dual-production to mono-production land use:

$$LER = \frac{Yield_a (duo)}{Yield_a (mono)} + \frac{Yield_b (duo)}{Yield_b (mono)} \quad (5)$$

In the equation, a and b denote cultivated crops and electricity, respectively.

The area losses that result from the uselessness of some land for cultivation because of the APV system’s mounting structure are another crucial factor to consider. This is especially true if the equipment being used leaves vacant areas of land between the pillars. These area losses outweigh the built-up area by a significant margin. On average, they account for approximately 10% [3,8]. As a result, we came to the following *LER* calculation:

$$LER = \frac{Yield_a (duo)}{Yield_a (mono)} + \frac{Yield_b (duo)}{Yield_b (mono)} - 10\% \quad (6)$$

An $LER < 1$ suggests that producing energy and crops together is not as productive as producing them separately, and an $LER > 1$ indicates higher productivity in the APV system when compared to mono-production. The LER is a useful tool for determining the practical potential of an APV system, even if it is not all-encompassing [3], and it is not only a measure of agricultural productivity but also an important tool for economic analysis in agriculture. By evaluating the economic impact of intercropping using the LER , farmers can make informed decisions that increase both their yields and profitability while promoting sustainable agricultural practices.

3. Results

3.1. Simulated Modified Radiation Below Different APV Designs

The annual changes (2013–2021) in the global radiation [MJ/m^2] of the different variants (V00–V07) are shown in Figure 11. The greatest loss is recorded for V06, with an average of $3000 \text{ MJ}/\text{m}^2$ per year, while V07 displays the smallest reduction in global radiation, with $4200 \text{ MJ}/\text{m}^2$. The factors that have an influence on the incoming irradiance below the APV modules are as follows: (i) The length of the rows: Longer rows (147.7 m) lead to higher reductions (e.g., V05 and V06), especially if they are installed at a 5 m height with a southern orientation. This is because more radiation can come from the sides (at the ends) of the rows when the rows are shorter. V04 (which is also a longer row) is an exception due to the vertical positioning of the panels. Although the positioning of V01 is vertical, it leads to a higher reduction in incoming radiation compared to V04 because the vertical height of the modules is larger. (ii) The distance between the rows: V03 shows one of the highest reductions, which is explained by the smaller distance between the rows. (iii) The orientation of the rows: modules oriented to the south cast much larger shadows at midday than those oriented towards the west and east. The lowest reduction in incoming solar radiation below the panels was obtained with scenario V07. The scenario assumes a short (11.98 m length) APV row with an N-S alignment (E-W orientation) of modules mounted on a tracker that orients the APV modules towards the east in the morning and towards the west in the evening. Because the APV modules at noon are in the horizontal position at a 5 m height and the row has an N-S alignment, this leads to very low shading because the sun's rays hit perpendicular to the direction of the row and the horizontal position of the modules leads to less shading than that of modules normally oriented towards the sun. An additional factor that leads to a higher incoming irradiance is the fact that the APV row in V07 has a length of only 11.98 m .

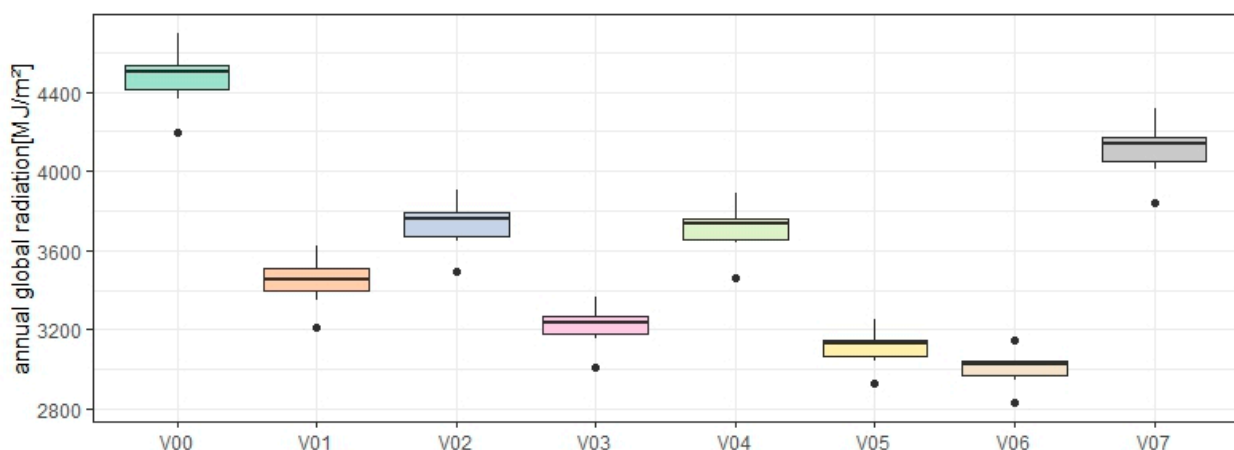


Figure 11. Annual changes (2013–2021) in global radiation [MJ/m^2] values of different variants (V00–V07). The vertical bars (whiskers) indicate the range of the different annual global radiation values from min. to max., while the black dots signify outliers that fall outside the expected range.

The reductions in the global radiation under the various APV designs for the different crop growing seasons are shown in Figure 12. With a reduction in global radiation of roughly -30% for spring barley and maize, it is evident that V01, V05, and V06 had the greatest impact. This finding is only recognizable in V05 and V06 for wheat ($<-30\%$ less global radiation) due to the extended winter wheat period. V07, which shows a reduction of less than 10% , had the least impact for the three crops. The reduction in V02 and V03 is between 15 and 20% for all three crops and is, therefore, in the middle of the range.

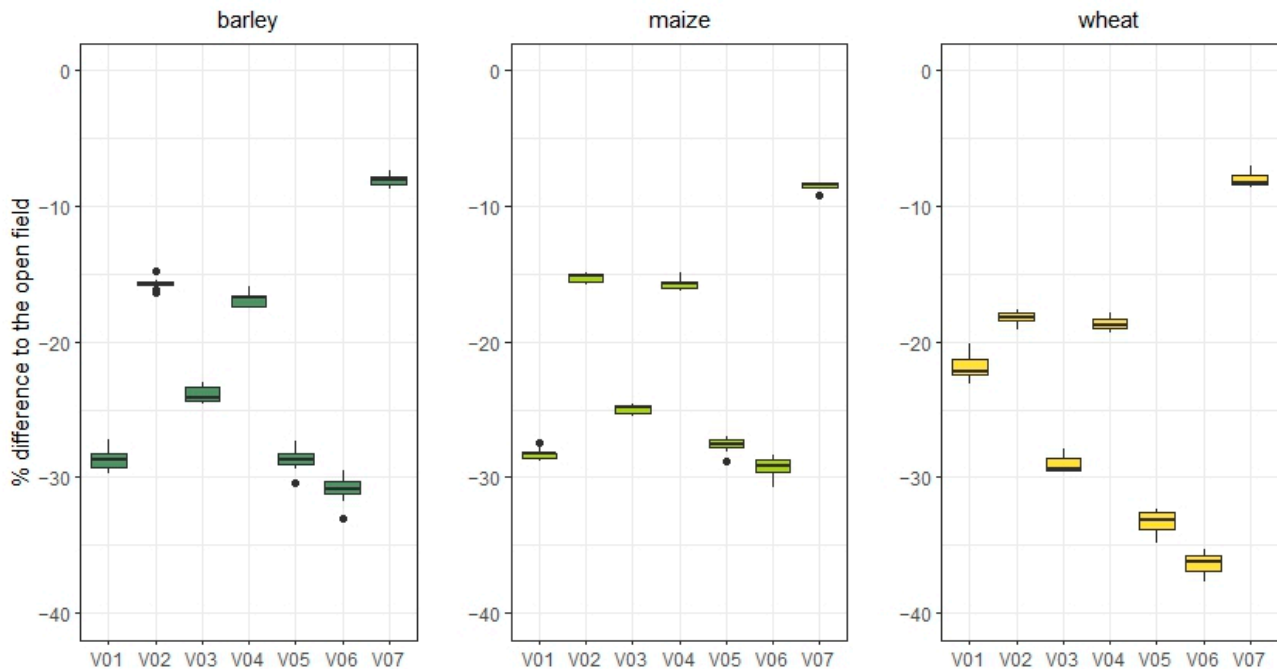


Figure 12. Percentage changes (2013–2021) in global radiation [MJ/m^2] of different APV design variants (V01–V07) compared to the open field (V00) for each crop (period from sowing to maturity/harvest). The vertical bars (whiskers) indicate the range of different annual global radiation values from min. to max., while the black dots signify outliers that fall outside the expected range.

3.2. Impacts of Different APV Designs on Crops

Among the individual APV design variants and crops, there are clear simulated differences in the shading effects on the crop biomasses and yields (Figure 13). The high variability in the maize, which is not as pronounced in the other two crops, is because maize (C4 plant) requires more radiation. Hence, the mean standard deviations (SDs) over all the variants are -8.8% for maize biomass and -14.8% for the yields. Spring barley, with SDs of -7.4% for biomass and -7.8% for yield, and winter wheat, with SDs of -6.4% for biomass and -3.5% for yield, are significantly lower. The greatest biomass and yield reductions are registered for maize and spring barley in V01, V03, V05, and V06 (biomasses and yields less than -20%), while V02 and V04 show reductions of approximately 12 – 15% . Winter wheat presents a different behavior. The biomass in V01–V04 is reduced by approximately 8 – 17% , and the grain yield is reduced by between 4 and 8% . With over 20% less biomass and over 10% less yield, V05 and V06 have the greatest yield loss effects on winter wheat.

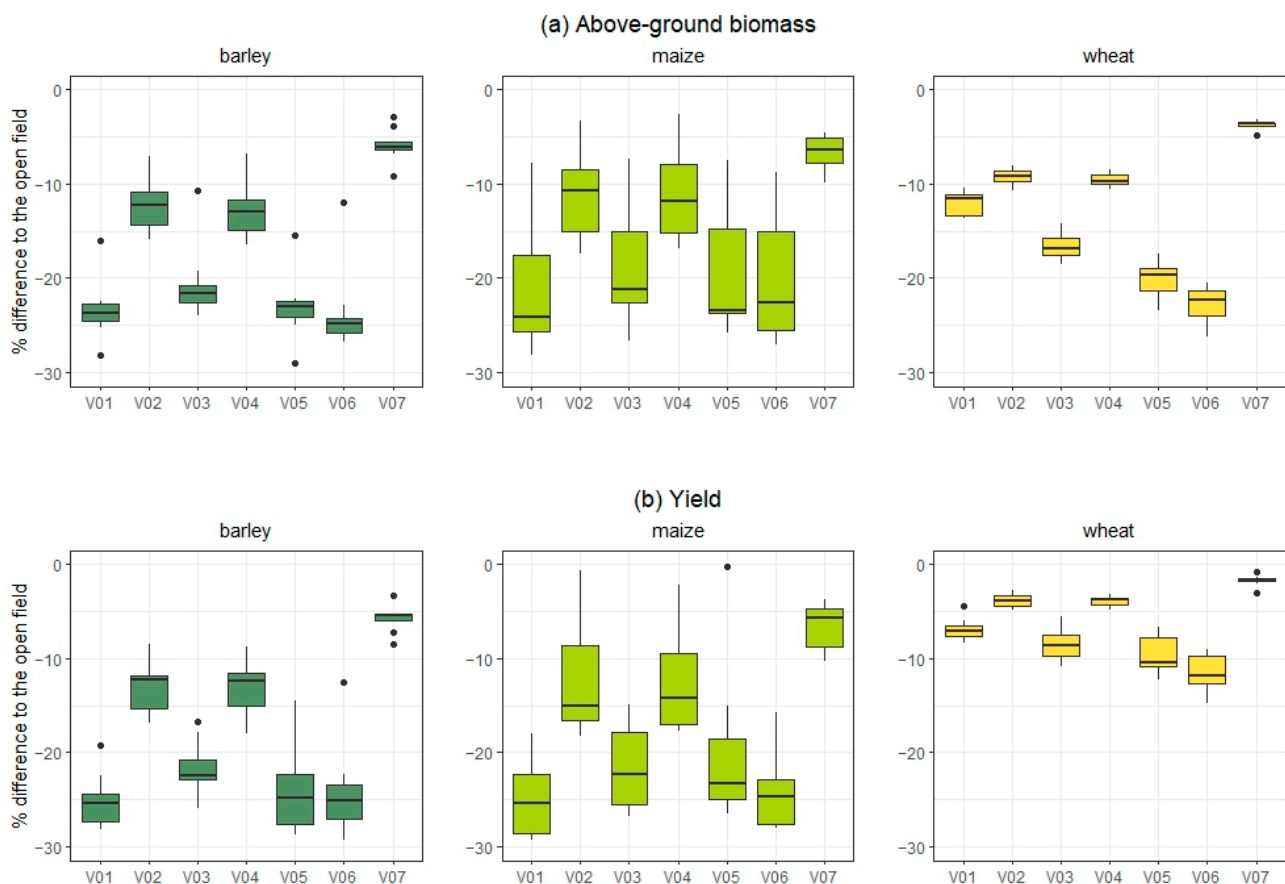


Figure 13. Simulated (a) above-ground biomass and (b) yield differences between APV design variants for spring barley, maize, and winter wheat compared to the open field in %. The vertical bars (whiskers) indicate the range of the above-ground biomass and yield differences from min. to max., while the black dots signify outliers which fall outside the expected range.

The correlation between the relative differences in the yields and the global radiation was examined in more detail using a regression equation (Figure 14). The relative yield reduction (%) relative to the open field (winter wheat: $r^2 = 0.83$; spring barley: $r^2 = 0.82$; and maize: not significant) increased with the amount of radiation reduction (%). Because maize reacted more strongly to absolute radiation reduction not only due to the APV design but also due to the weather, there is a greater spread of the simulated annual yields in each variant, and, therefore, no significant correlation to the relative radiation reduction.

If the simulated evapotranspiration with the DSSAT is also considered, the following can be determined: the higher the relative yield difference (%) to that of the open field, the higher the relative differences in the simulated evapotranspiration (%) to that of the open field (maize: $r^2 = 0.81$; spring barley: $r^2 = 0.86$; and winter wheat: $r^2 = 0.61$) (Figure 15).

Figure 16 breaks down the reductions in the above-ground biomass and grain yield for spring barley for the individual years analyzed. The variants V01, V03, V05, and V06 had the greatest negative impacts on the above-ground biomass and grain yield in spring barley, and V07 had the smallest negative impact (Figure 16). The lowest yield deviations were recorded in the warm and dry vegetation period (2015) (see Figure 1). The years 2017, 2018, and 2021 were also hot and warm, but the yield reductions were quite high in every variant. The wettest growing seasons were 2013, 2016, and 2019, which showed large deviations in total. V05 and V06 presented the greatest deviations in the above-ground biomass and yield for 2016 and 2019.

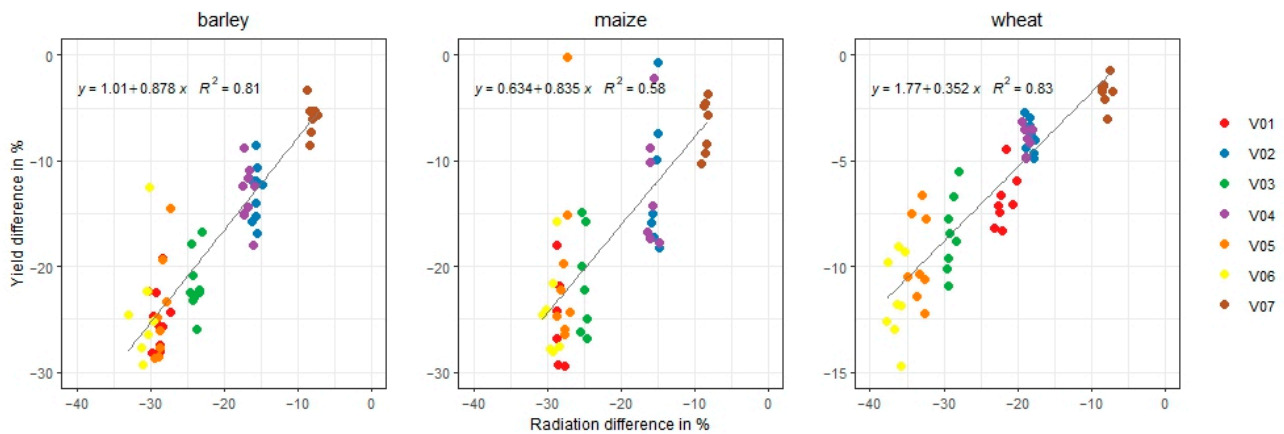


Figure 14. Relative yield differences vs. relative global radiation differences in the different scenarios (V01–V07) compared to the open field.

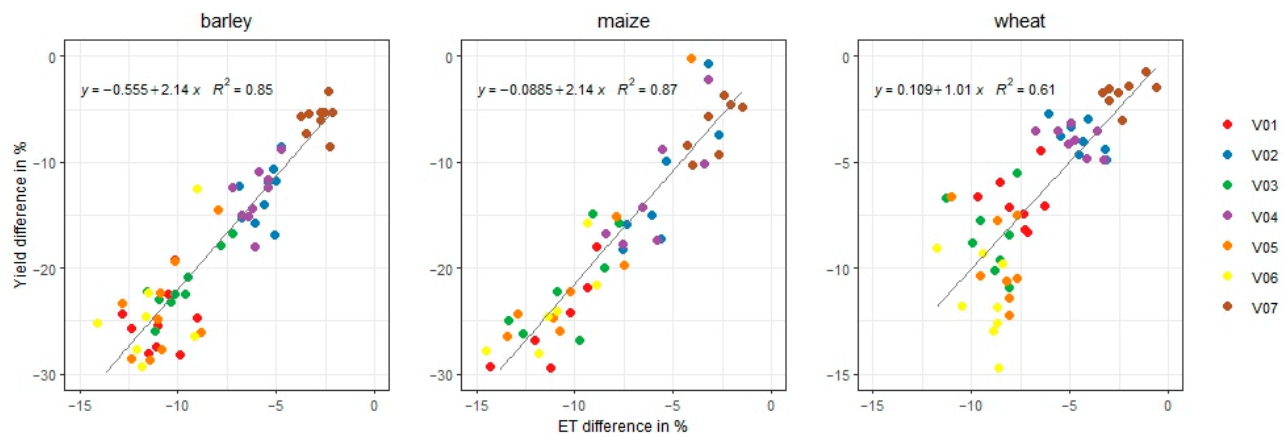


Figure 15. Relative difference in yields vs. relative difference in evapotranspiration of the different scenarios (V01–V07) compared to the open field.

V01, V03, V05, and V06 displayed the greatest reductions in the biomass and yield for maize (Figure 17). During the drier growing seasons (2015 and 2017) (Figure 1), these decreases were the lowest and, in some cases, even showed higher biomasses and/or yields than in the open field. In 2015, a higher above-ground biomass for maize (around +8%) was simulated under the APVs in V02, V04, and V07, as well as higher yields (>10%) in V01, V03, V05, V06, and V07. With a total of 124 mm during the maize vegetation period, this was the driest year on record; with 224 mm, 2017 had the second driest growing season. In the wetter years (especially 2013, 2014, and 2016, with more than 315 mm of precipitation during the growing season), the biomass and grain yield were significantly lower. V07 demonstrated the lowest biomass and yield reductions in almost all years for maize.

The smallest differences in grain yield were simulated for winter wheat compared to the other two crops, with a more pronounced decrease in the above-ground biomass. The deviations between the years within the variants were also smaller. The largest decreases could be expected in V03, V05, and V06, although the annual fluctuations were rather small. V02, V04, and V07 showed the least influence, with up to −10% biomass and −5% yield reductions (Figure 18).

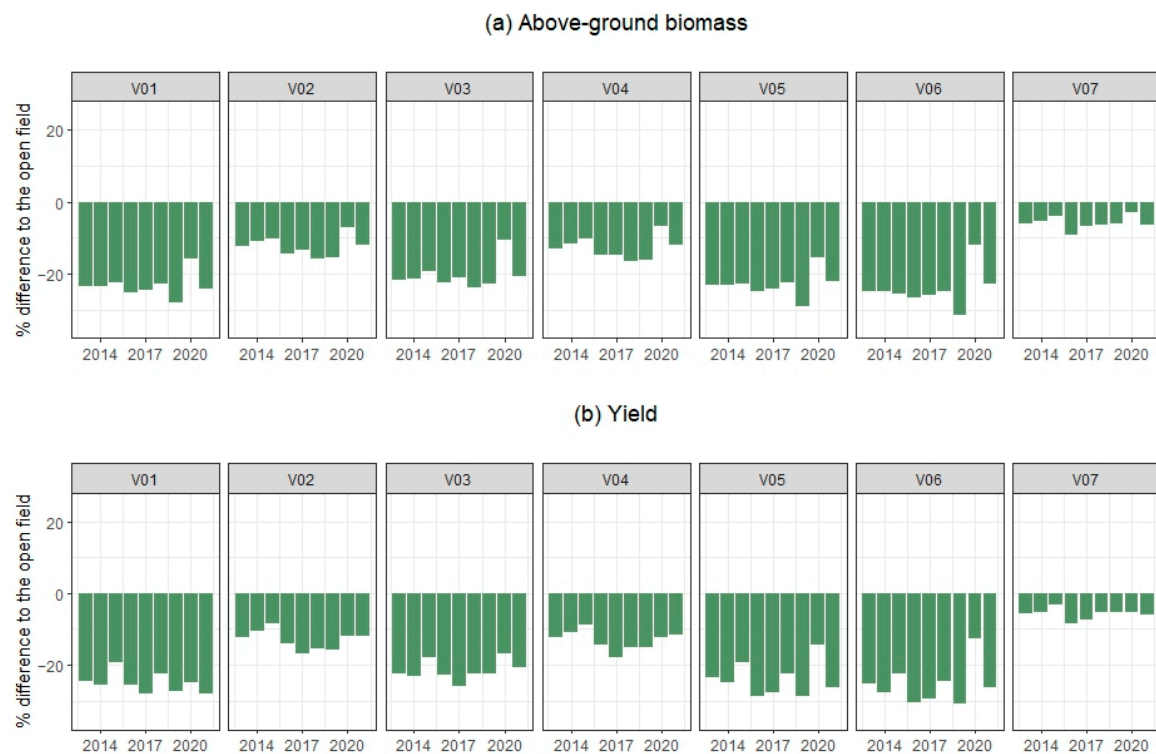


Figure 16. Annual simulated spring barley (a) above-ground biomass and (b) yield deviation relative to the open field.

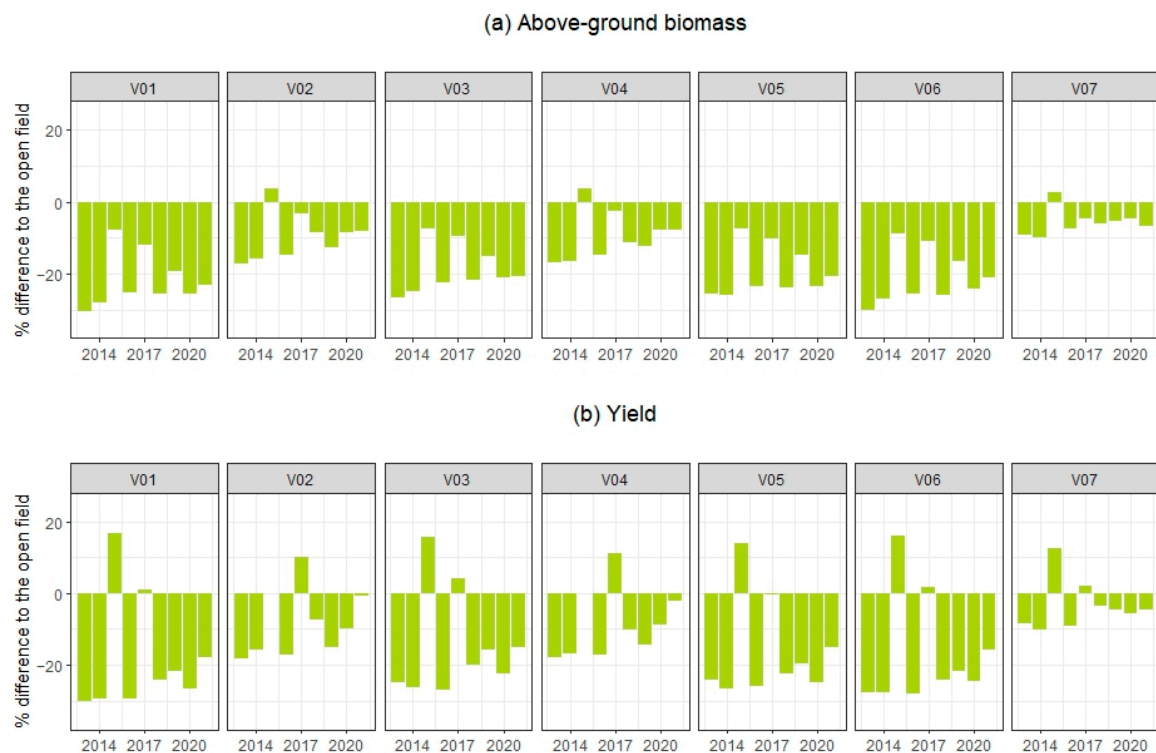


Figure 17. Simulated annual (a) above-ground biomass and (b) grain yield deviation of maize relative to the open field.

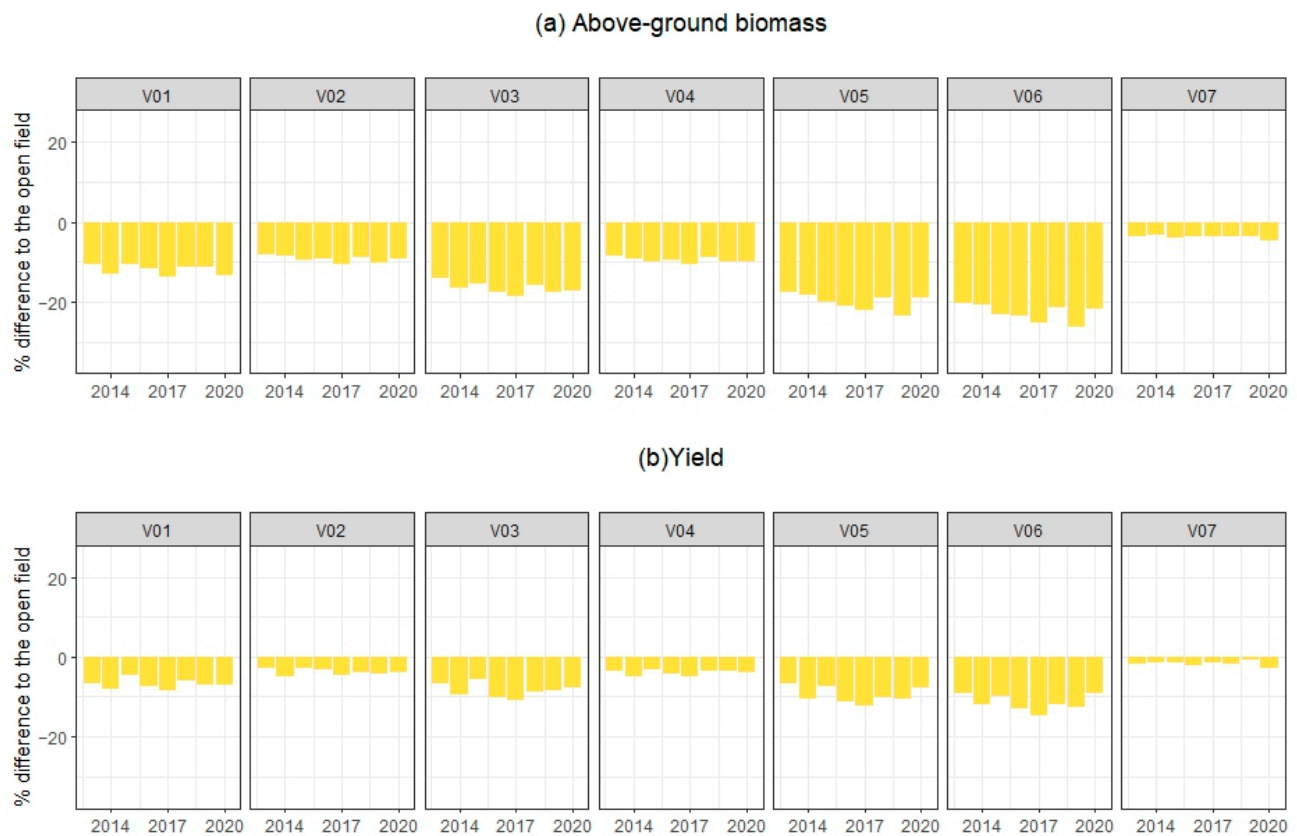


Figure 18. Simulated annual (a) above-ground biomass and (b) yield deviation of winter wheat relative to the open field.

3.3. Comparison of Simulated Crop and Energy Yields of Various APV Systems

The average crop and energy yields as well as the *LERs* were determined to establish a comparison between the potential yields and electricity profit per scenario (Table 3).

Table 3. Energy production, crop yields, and land equivalent ratios (*LERs*) for the different scenarios (V00–V07). PV: field with only PV panels.

Scenario	Energy Production per kWh/ha/a	PV <i>LER</i>	Maize Yield kg/ha	Maize <i>LER</i>	Barley Yield kg/ha	Barley <i>LER</i>	Wheat Yield kg/ha	Wheat <i>LER</i>	Maize + PV <i>LER</i>	Barley + PV <i>LER</i>	Wheat + PV <i>LER</i>
V00	---	0	6188	1	4076	1	5680	1			
V01	359,369	0.32	4878	0.79	3042	0.75	5290	0.93	1.00	0.96	1.13
V02	268,699	0.24	5687	0.92	3541	0.87	5463	0.96	1.04	1.00	1.08
V03	275,242	0.24	5105	0.82	3176	0.78	5199	0.92	0.95	0.92	1.04
V04	310,271	0.28	5676	0.92	3533	0.87	5458	0.96	1.08	1.03	1.12
V05	289,033	0.26	5023	0.81	3067	0.75	5134	0.90	0.96	0.91	1.05
V06	289,033	0.26	4956	0.80	2999	0.74	5025	0.88	0.95	0.90	1.03
V07	280,170	0.25	5885	0.95	3833	0.94	5584	0.98	1.08	1.07	1.11
PV	1,117,425	1	0	0	0	0	0	0			

The energy production and the resulting financial yields were calculated for the different APV system designs. Taking the module width and row length into account, we calculated the number of PV modules in one row. Then, we calculated the maximum number of rows possible in a 1 ha area. For the PV row length of 11.89 m, we assumed an area of 769 × 13 m, which allowed 64 rows with a distance between the PV rows of 12 m and 76 rows with a distance between the PV rows of 10 m. For the row length of 147.7 m, we assumed an area of 149 × 67 m, which allowed five rows. Because we knew the number

of PV modules in one row, we could easily determine the total number of PV modules in a 1 ha area. The nominal output of one PV module was multiplied with the number of PV modules to obtain the total KwP of the entire PV system. Because the production of Kwh per KwP and year had already been calculated for each scenario, we could multiply this last value with the nominal KwP output of all the PV modules and obtain the energy production of the entire PV system. V01 had the highest total energy production because the bifacial PV modules had a higher KwP nominal output of 410 Wp compared to the 290 Wp for the other monocrystalline PV modules. The yield from the APV system was approximately one-third of the yield from the open-field system (see the PV *LER* column) without agriculture (for which the distance between the rows was approximately one-third of that for the APV).

For the crop yield, the mean value of the 9-year simulations was used for each variant (maize/barley/wheat yield (kg/ha)). V00 was applied as the variant for which only one monoculture grew on a 1 ha field. The other variants (V01–V07) showed polyculture grain yields. V07 had the highest *LER* for all crops, with over 0.93, followed by V02 and V04 (maize/barley/wheat *LER*s). Overall, winter wheat had the highest *LER* values, compared to spring barley, with values of 0.75 and below (V01, V05, and V06). Maize had a range from 0.79 (V01) to 0.95 (V07). Combining the energy and crop yields, V07 with an $LER \geq 1.07$ had the highest values (*LER* maize/barley/wheat + PV). A higher productivity of the APV system compared to mono-production was shown for all the winter wheat variants. For maize, in addition to V07, V02, and V04, and, for spring barley, V04, the *LER* values were above 1.

4. Discussion

APV systems optimize land use through the simultaneous production of food and energy and can therefore lead to, e.g., improved land use efficiency and microclimatic benefits for crops (e.g., less heat stress) [6,40]. Economically, this can contribute to agricultural incomes through energy sales and lower energy costs, and it can create new jobs and improve access to energy in rural areas. However, APVs can also have some unfavorable consequences: some crops that require a lot of light may have decreased crop yields due to the ability of solar panels to block sunlight [11]. When energy production takes precedence over food production in densely populated areas, particularly when land is limited, tensions may arise. By reducing rainfall and evaporation beneath the panels, the installation of solar panels may have an impact on the soil conditions and water distribution [41]. For smaller farms, the large upfront costs associated with APV system installation and maintenance may be a barrier. When solar panels negatively alter the environment, especially in places of scenic or cultural significance, the local populace may reject them. The challenge of harmonizing these factors with the benefits is crucial for successful APV introduction. The aim of our use case was to identify preliminary optimal combinations of the selected APV systems with relevant crop types, considering annually varying weather conditions, to maximize crop yields and energy production in the drought-prone region of north-eastern Austria.

In this study, a new method for the calculation of shading under APV systems was developed and demonstrated for a crop simulation use case. This method relies on processing fisheye images to draw the outlines of PV systems. Using image digitalization and radiation models, the radiance for each solid angle of the sky hemisphere above and below an APV system at the experimental site was determined, which enabled a precise determination of the daily radiation cycle below the APVs and allowed us to determine the influences of different APV system geometries on the ground-incident solar radiation. A calibration was made between the simulations and radiation measurements for a test site with one APV design.

The simulations for three representative arable crops in Austria—winter wheat, spring barley, and maize—which are part of most regional crop rotations and are representative of one winter crop, one spring crop, and one summer crop, respectively, showed the

following results for a multi-year (2003–2021) weather period representative of eastern Austria. The annual above-ground biomass and grain yield reduction and variability were the greatest for the maize with respect to the APV design and annual weather conditions, reaching a yield reduction of up to 25%, with large differences between the APV designs and annual weather conditions. However, a very slight increase in the grain yield (up to 16%) was observed in dry years compared to the open-field conditions. This increasing yield effect could not be simulated for the other two crops. For spring barley, the annual grain yield reduction with respect to the APV design and annual weather conditions was approximately 10–25%, with greater yield reduction occurring in the humid/low-radiation growing season (April–June). Winter wheat showed the smallest effects, reaching an annual yield reduction (with respect to the APV design and weather conditions) of only up to 10% due to shading, and, thus, reduced the photosynthetic performance.

Additional and/or corroborating findings from the literature (e.g., [6,42,43]) are consistently reported for the European climate region: depending on the APV design, a shading effect and crop yield reductions of up to a maximum of 50% but mostly in the range of 0–30% at larger APV row spacings and heights have been reported [44]. This is also confirmed by our simulations.

The limitation of the applied use case of our study is that the following microclimatic changes and effects known from the literature were not or only partially taken into account in our simulation (e.g., [16,45]) (evapotranspiration due to radiant energy was considered in the crop model): (i) the decrease in the daily maximum temperatures in the crops (approx. 1 °C) and soil temperatures while the daily mean temperature remained constant, which means more balanced temperatures under APVs; and (ii) the increase in soil water (due to reduced evaporation and the windbreak effect), resulting, in very dry years, in generally decreasing yield differences compared to the open field, and the yields under the APV sometimes being higher per unit area than in the open field (as reported in the literature for several crops (e.g., [6,11,45]) and achieved in our simulations solely through the radiation effect for maize).

In our study, the windbreak effects of the modules were not considered, and the positive yield effect in dry years was probably underestimated, as a comparison to the literature results suggests [6,45]. Furthermore, due to the lower daily maximum temperatures caused by the shading effects, less heat stress-related damage under APV designs can also be expected during heatwaves. Considering the ongoing climate change with increasing dry periods, these microclimatic effects can be seen as a positive effect, especially in drought-prone regions.

Overall, in cold/humid/cloudy weather periods during the growing season, the negative yield effects are more pronounced than during the dry/hot growing periods: i.e., it is possible that summer crops such as maize benefit the most from an optimized microclimate, although crop-specific differences with respect to temperature optima, drought resistance, light requirements, etc., must be considered, the differentiation of which is still clearly a subject of future research.

As a crop, winter wheat had the least impact on the yields due to APV shading, while spring barley and maize had significantly stronger impacts. The lowest grain yield decrease was achieved for all three crops in the V07 APV design scenario, which is also the scenario for which the highest *LER* was calculated. In scenario V07, the modules were oriented to the east at a height of 5 m and mounted on trackers, and the lowest global radiation attenuations were also calculated in this scenario. However, the rows were (11.98 m) shorter, which means that it was also a smaller APV system with less total energy production (sum of energy production of all single APV modules). In general, a shorter row leads to smaller reductions in the incident solar radiation below the APV and in the crop yields. However, at the same time, it also means that it is a smaller APV system with less total energy production. Scenario V04 showed a good performance in terms of the electricity production and agricultural yield ($LER \geq 1.03$), although it comprised a longer row with a 147.7 m length. The key factors here were the tracker for the electricity yield

and the east–west orientation, as well as the sufficient distance between the APV rows for the agricultural yield. The correct use of a tracker on APV fields seems to be one of the key factors for optimizing agricultural yields and electricity production.

However, farmers are primarily interested in the financial aspects of APV installation. Using the feed-in tariff (the mean value of the last year was 9.4 c/KWh) specified by the energy agency e-control (<https://www.e-control.at/marktteilnehmer/oeko-energie/marktpreis>; accessed on 1 October 2024), we calculated the total financial gain of the PV operator over one year for a 1 ha field, which roughly amounted to a sum between EUR 25,000 and 33,000. As a rule, farmers in Austria do not usually operate PV systems themselves, but, rather, this is carried out by the energy companies, paying a lease (rental) of around EUR 3500 per year and hectare to the farmer.

5. Conclusions

Increasing numbers of APV designs and their modifications have increased the demand for effective calculation methods for the modification of the radiation regime and microclimatic conditions to fulfill crop demands and optimize both crop productivity and energy production at the same time. In our study, we applied a new method for the calculation of the shading effect below various APV systems and demonstrated its application in crop modeling. The optimal conditions for carrying out the below-APV radiation calculations are precise data on the direct and diffuse components of the incident radiation above the PV systems. If data are missing, model calculations can also be used; however, this could lead to higher uncertainty. In the crop simulation, we did not consider further microclimatic modifications, which are strongly determined by the APV system design. Here, measured meteorological and soil moisture data are still rare or missing for the development or use of sound microclimatic modification models. Another important task for future research is the development of models to estimate the spectral modification of the radiation regime below APV designs. A precise economic analysis is also necessary for stakeholder decisions.

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References

- Shboul, B.; Zayed, M.E.; Ashraf, W.M.; Usman, M.; Roy, D.; Irshad, K.; Rehman, S. Energy and economic analysis of building integrated photovoltaic thermal system: Seasonal dynamic modeling assisted with machine learning-aided method and multi-objective genetic optimization. *Alex. Eng. J.* **2024**, *94*, 131–148. [\[CrossRef\]](#)
- Goetzberger, A.; Zastrow, A. On the Coexistence of Solar-Energy Conversion and Plant Cultivation. *Int. J. Sol. Energy* **1982**, *1*, 55–69. [\[CrossRef\]](#)
- Asa'a, S.; Reher, T.; Rongé, J.; Diels, J.; Poortmans, J.; Radhakrishnan, H.S.; van der Heide, A.; Van de Poel, B.; Daenen, M. A multidisciplinary view on agrivoltaics: Future of energy and agriculture. *Renew. Sustain. Energy Rev.* **2024**, *200*, 114515. [\[CrossRef\]](#)
- Bogdanski, A.; Dubois, O.; Jamieson, C.; Krell, R. *Making Integrated Food-Energy Systems Work for People and Climate*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2011; p. 45.
- Vidotto, L.C.; Schneider, K.; Morato, R.W.; do Nascimento, L.R.; Rütther, R. An evaluation of the potential of agrivoltaic systems in Brazil. *Appl. Energy* **2024**, *360*, 122782. [\[CrossRef\]](#)
- Weselek, A.; Bauerle, A.; Hartung, J.; Zikeli, S.; Lewandowski, I.; Högy, P. Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. *Agron. Sustain. Dev.* **2021**, *41*, 59. [\[CrossRef\]](#)
- Shayanmehr, S.; Porhajašová, J.I.; Babošová, M.; Sabouhi Sabouni, M.; Mohammadi, H.; Rastegari Henneberry, S.; Shahnoushi Foroushani, N. The Impacts of Climate Change on Water Resources and Crop Production in an Arid Region. *Agriculture* **2022**, *12*, 1056. [\[CrossRef\]](#)
- Laub, M.; Pataczek, L.; Feuerbacher, A.; Zikeli, S.; Högy, P. Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: A meta-analysis. *Agron. Sustain. Dev.* **2022**, *42*, 51. [\[CrossRef\]](#)
- Ruberti, I.; Sessa, G.; Cioffi, A.; Possenti, M.; Carabelli, M.; Morelli, G. Plant adaptation to dynamically changing environment: The shade avoidance response. *Biotechnol. Adv.* **2012**, *30*, 1047–1058. [\[CrossRef\]](#)
- Ouzounis, T.; Rosenqvist, E.; Ottosen, C.-O. Spectral Effects of Artificial Light on Plant Physiology and Secondary Metabolism: A Review. *HortScience Horts* **2015**, *50*, 1128–1135. [\[CrossRef\]](#)
- Touil, S.; Richa, A.; Fizir, M.; Bingwa, B. Shading effect of photovoltaic panels on horticulture crops production: A mini review. *Rev. Environ. Sci. Bio/Technol.* **2021**, *20*, 281–296. [\[CrossRef\]](#)
- Dupraz, C. Assessment of the ground coverage ratio of agrivoltaic systems as a proxy for potential crop productivity. *Agrofor. Syst.* **2023**. [\[CrossRef\]](#)
- Gnayem, N.; Magadley, E.; Haj-Yahya, A.; Masalha, S.; Kabha, R.; Abasi, A.; Barhom, H.; Matar, M.; Attrash, M.; Yehia, I. Examining the effect of different photovoltaic modules on cucumber crops in a greenhouse agrivoltaic system: A case study. *Biosyst. Eng.* **2024**, *241*, 83–94. [\[CrossRef\]](#)
- Trommsdorff, M.; Kang, J.; Reise, C.; Schindele, S.; Bopp, G.; Ehmann, A.; Weselek, A.; Högy, P.; Obergfell, T. Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany. *Renew. Sustain. Energy Rev.* **2021**, *140*, 110694. [\[CrossRef\]](#)
- Jäger, M.; Vaccaro, C.; Boos, J.; Junghardt, J.; Strebel, S.; Anderegg, D.; Rohrer, J.; Schibli, B. *Machbarkeitsstudie Agri-Photovoltaik in der Schweizer Landwirtschaft*; ZHAW Zürcher Hochschule für Angewandte Wissenschaften: Winterthur, Switzerland, 2022.
- Marrou, H.; Dufour, L.; Wery, J. How does a shelter of solar panels influence water flows in a soil–crop system? *Eur. J. Agron.* **2013**, *50*, 38–51. [\[CrossRef\]](#)
- Jamil, U.; Hickey, T.; Pearce, J.M. Solar energy modelling and proposed crops for different types of agrivoltaics systems. *Energy* **2024**, *304*, 132074. [\[CrossRef\]](#)
- Sarr, A.; Soro, Y.M.; Tossa, A.K.; Diop, L. A new approach for modelling photovoltaic panel configuration maximizing crop yield and photovoltaic array outputs in agrivoltaics systems. *Energy Convers. Manag.* **2024**, *309*, 118436. [\[CrossRef\]](#)
- Kim, S.; Kim, S.; An, K. An integrated multi-modeling framework to estimate potential rice and energy production under an agrivoltaic system. *Comput. Electron. Agric.* **2023**, *213*, 108157. [\[CrossRef\]](#)
- Prakash, V.; Lunagaria, M.M.; Trivedi, A.P.; Upadhyaya, A.; Kumar, R.; Das, A.; Kumar Gupta, A.; Kumar, Y. Shading and PAR under different density agrivoltaic systems, their simulation and effect on wheat productivity. *Eur. J. Agron.* **2023**, *149*, 126922. [\[CrossRef\]](#)
- Witzmann, S.; Gollob, C.; Kraßnitzer, R.; Ritter, T.; Tockner, A.; Schume, H.; Nothdurft, A. Modeling of solar radiation and sub-canopy light regime on forest inventory plots of mixed conifer and deciduous temperate forests using point clouds from personal laser scanning. *For. Ecol. Manag.* **2024**, *569*, 122166. [\[CrossRef\]](#)
- Wang, Q.; Peng, L.L.H.; Jiang, W.; Yin, S.; Feng, N.; Yao, L. Urban form affects the cool island effect of urban greenery via building shadows. *Build. Environ.* **2024**, *254*, 111398. [\[CrossRef\]](#)
- GeoSphere. Messstationen Tagesdaten v2. Available online: <https://data.hub.geosphere.at/> (accessed on 8 August 2024).
- Olefs, M.; Baumgartner, D.J.; Obleitner, F.; Bichler, C.; Foelsche, U.; Pietsch, H.; Rieder, H.E.; Weihs, P.; Geyer, F.; Haiden, T.; et al. The Austrian radiation monitoring network ARAD—Best practice and added value. *Atmos. Meas. Tech.* **2016**, *9*, 1513–1531. [\[CrossRef\]](#)
- Huld, T.; Müller, R.; Gambardella, A. A new solar radiation database for estimating PV performance in Europe and Africa. *Sol. Energy* **2012**, *86*, 1803–1815. [\[CrossRef\]](#)
- European Commission. Photovoltaic Geographical Information System (PVGIS). Available online: https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en (accessed on 8 August 2024).

27. Valentin Software. PV*SOL Premium—The Design and Simulation Software for Photovoltaic Systems. Available online: <https://valentin-software.com/en/products/pvsol-premium/> (accessed on 8 August 2024).
28. Tsubo, M.; Walker, S. Relationships between photosynthetically active radiation and clearness index at Bloemfontein, South Africa. *Theor. Appl. Climatol.* **2005**, *80*, 17–25. [\[CrossRef\]](#)
29. Gueymard, C.A. Spectral Circumsolar Radiation Contribution To CPV. *AIP Conf. Proc.* **2010**, *1277*, 316–319. [\[CrossRef\]](#)
30. Weihs, P.; Webb, A.R.; Hutchinson, S.J.; Middleton, G.W. Measurements of the diffuse UV sky radiance during broken cloud conditions. *J. Geophys. Res. Atmos.* **2000**, *105*, 4937–4944. [\[CrossRef\]](#)
31. Jones, J.W.; Hoogenboom, G.; Porter, C.H.; Boote, K.J.; Batchelor, W.D.; Hunt, L.A.; Wilkens, P.W.; Singh, U.; Gijsman, A.J.; Ritchie, J.T. The DSSAT cropping system model. *Eur. J. Agron.* **2003**, *18*, 235–265. [\[CrossRef\]](#)
32. Hoogenboom, G.; Porter, C.H.; Boote, K.J.; Shelia, V.; Wilkens, P.W.; Singh, U.; White, J.W.; Asseng, S.; Lizaso, J.I.; Moreno, L.P.; et al. The DSSAT crop modeling ecosystem. In *Advances in Crop Modelling for a Sustainable Agriculture*; Burleigh Dodds Science Publishing: Sawston, UK, 2019.
33. Hoogenboom, G.; Porter, C.H.; Shelia, V.; Boote, K.J.; Singh, U.; White, J.W.; Pavan, W.; Oliveira, F.A.A.; Moreno-Cadena, L.P.; Lizaso, J.I.; et al. *Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.8.2*; DSSAT Foundation: Gainesville, FL, USA, 2023.
34. Thaler, S.; Eitzinger, J.; Trnka, M.; Dubrovsky, M. Impacts of climate change and alternative adaptation options on winter wheat yield and water productivity in a dry climate in Central Europe. *J. Agric. Sci.* **2012**, *150*, 537–555. [\[CrossRef\]](#)
35. Eitzinger, J.; Trnka, M.; Semerádová, D.; Thaler, S.; Svobodová, E.; Hlavinka, P.; Šiška, B.; Takac, J.; Malatinská, L.; Nováková, M.; et al. Regional climate change impacts on agricultural crop production in Central and Eastern Europe—Hotspots, regional differences and common trends. *J. Agric. Sci.* **2012**, *151*, 787–812. [\[CrossRef\]](#)
36. Thaler, S.; Formayer, H.; Kubu, G.; Trnka, M.; Eitzinger, J. Effects of Bias-Corrected Regional Climate Projections and Their Spatial Resolutions on Crop Model Results under Different Climatic and Soil Conditions in Austria. *Agriculture* **2021**, *11*, 1029. [\[CrossRef\]](#)
37. Mead, R.; Willey, R.W. The Concept of a ‘Land Equivalent Ratio’ and Advantages in Yields from Intercropping. *Exp. Agric.* **1980**, *16*, 217–228. [\[CrossRef\]](#)
38. Dupraz, C.; Marrou, H.; Talbot, G.; Dufour, L.; Nogier, A.; Ferard, Y. Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renew. Energy* **2011**, *36*, 2725–2732. [\[CrossRef\]](#)
39. Willey, R.W. Evaluation and Presentation of Intercropping Advantages. *Exp. Agric.* **1985**, *21*, 119–133. [\[CrossRef\]](#)
40. Fagnano, M.; Fiorentino, N.; Visconti, D.; Baldi, G.M.; Falce, M.; Acutis, M.; Genovese, M.; Di Blasi, M. Effects of a Photovoltaic Plant on Microclimate and Crops’ Growth in a Mediterranean Area. *Agronomy* **2024**, *14*, 466. [\[CrossRef\]](#)
41. Widmer, J.; Christ, B.; Grenz, J.; Norgrove, L. Agrivoltaics, a promising new tool for electricity and food production: A systematic review. *Renew. Sustain. Energy Rev.* **2024**, *192*, 114277. [\[CrossRef\]](#)
42. Weselek, A.; Ehmann, A.; Zikeli, S.; Lewandowski, I.; Schindele, S.; Högy, P. Agrophotovoltaic systems: Applications, challenges, and opportunities. A review. *Agron. Sustain. Dev.* **2019**, *39*, 35. [\[CrossRef\]](#)
43. Ferrara, G.; Boselli, M.; Palasciano, M.; Mazzeo, A. Effect of shading determined by photovoltaic panels installed above the vines on the performance of cv. Corvina (*Vitis vinifera* L.). *Sci. Hortic.* **2023**, *308*, 111595. [\[CrossRef\]](#)
44. Barron-Gafford, G.A.; Pavao-Zuckerman, M.A.; Minor, R.L.; Sutter, L.F.; Barnett-Moreno, I.; Blackett, D.T.; Thompson, M.; Dimond, K.; Gerlak, A.K.; Nabhan, G.P.; et al. Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat. Sustain.* **2019**, *2*, 848–855. [\[CrossRef\]](#)
45. Kanzler, M.; Böhm, C.; Mirck, J.; Schmitt, D.; Veste, M. Microclimate effects on evaporation and winter wheat (*Triticum aestivum* L.) yield within a temperate agroforestry system. *Agrofor. Syst.* **2019**, *93*, 1821–1841. [\[CrossRef\]](#)

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