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Agrivoltaics Crop Yield Modeling

Quantifying the Effects of Light Limitations on Crop Growth

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Abstract. Agrivoltaics (APV) combine agriculture and photovoltaic (PV) energy production on the same land and have the potential to provide several synergies for both production systems. Moving towards large-scale commercial implementation, synergies and trade-offs need to be quantified. Various APV designs exist and have been studied in field experiments in the past. In addition to PV design choices, differences respecting the crops grown, the soil conditions and the climatic conditions are known to affect crop yields. However, it is unclear how planned APV sites with conditions that differ from the known research sites will perform. This poses challenges in terms of assessing the implications for both farmers and APV planners. Therefore, we developed a framework for simulating impacts of APV shading effects on crop yields. A new APV shading model is developed to specifically match the needs of the PROMET crop model, which is capable of worldwide simulations for a large range of crop types. When compared to results from the state-of-the art bifacial radiance raytracing model, similar trends and magnitudes in irradiance reductions have been observed. Agricultural yield prediction simulations for a planned BayWa r.e. APV project in France were used as a test case. The simulation results showed large differences between one-in-portrait and two-in-portrait trackers. The simulated crop yields for the site remain only within an acceptable range for winter wheat and rapeseed with 1P trackers. While the shading model and PROMET have already been tested individually, a more in-depth validation of the entire framework is planned for the near future, when data for planned systems becomes available. The addition of the APV shading model expands capabilities of the PROMET crop model towards APV simulation and allows for future development of advanced APV-related data products.

Keywords: Environmental Modeling, Crop Modeling, Crop Yields, PROMET

1. Introduction

In the context of climate change and a growing world population, resilient energy and food production systems are of great importance. Photovoltaic (PV) energy production does not rely on reservoirs or cooling water and could provide enhanced resilience under uncertain water resource conditions [1]. However, large-scale expansion of PV energy production requires land, which raises growing concerns about emerging land use conflicts over valuable farmland. Agrivoltaics (APV) refer to the simultaneous use of land for both agricultural food production and PV energy production and have the potential to provide several synergies for both production systems [1], [2], [3]. PV modules are arranged in a way that allows for the use of agricultural machinery in between, next to or below the PV modules. These concepts have been implemented at research sites with differing APV designs in the past. Due to the PV modules, crops are shaded in a non-uniform way. The impacts of shading effects are crop-specific and growth-stage-dependent and are known to influence crop yields and quality [3]. In addition, field studies have reported differing responses caused by the crop varieties grown, the soil conditions and the climatic conditions [3]. However, it remains unclear to which extent results from these known study sites can be transferred to newly planned APV sites, which poses challenges for both farmers and APV planners. Moving towards large-scale commercial implementation, synergies and trade-offs that come with APV need to be quantified in order to allow for optimized design choices as well as adjusted management practices. Therefore, a framework for simulating impacts of APV shading effects on crop yields is needed. Combining an APV light simulation approach with the well-validated PROMET crop model [4] enables worldwide simulations for a large range of crops and variable APV layouts under various climatic conditions. In this study, the newly developed framework is applied for the first time to support the planning of a BayWa r.e. APV project site in France.

2. Methods

2.1 Models

The crop yield prediction is based on the PROMET model [4] and includes a newly developed APV light simulation. This geometric light simulation tool (VISTA Agri-PV shading model) modifies the direct and diffuse irradiance for observation points with a 10 cm spacing for each hour, which corresponds to the temporal resolution of the PROMET crop model. PROMET is capable of simulating spatially distributed land surface processes (such as actual land surface water and energy balance, dynamic vegetation development, soil moisture, soil temperature and soil nutrients dynamics) from the field scale to the global scale [5], [6], [7]. Due to the holistic approach of the model, changes within one process (e.g. in the irradiance inputs) affect other processes (e.g. soil evaporation and crop transpiration). In combination with the capability to predict spatial crop yield patterns within one field at hourly temporal resolution, this should in theory make PROMET very suitable for simulating processes altered by APV on the sub-field scale. The PROMET crop model has been validated in several studies in the past and is regularly used on an operational basis for yield prediction products for different regions and climate conditions (https://ypsilon.services). Radiative transfer within the vegetation's canopy is handled within PROMET and requires top of canopy direct and diffuse irradiance input data (among other meteorological inputs) for the entire growing season [5], [6], [7].

In contrast, state of the art ray-tracing models (such as bifacial radiance [8]) simulate global irradiance. Splitting global irradiance outputs into a direct and a diffuse component based on cloud cover is not feasible here, since the effect of APV on the direct to diffuse ratio would be neglected. In addition, running a computationally expensive model in 10 cm spatial resolution for every hour of the entire growing season would require a lot of computation power. Therefore, the VISTA Agri-PV shading model was developed to fit the specific needs of the crop model. It uses geometry-based approaches to estimate direct and diffuse irradiance for the whole growing season in the required temporal and spatial resolution in a computationally efficient way: APV-modified direct irradiances are calculated using PROMET's solar position algorithm in combination with line-plane intersection to determine the shaded areas. The diffuse irradiances altered by APV are determined using l'Huilier's theorem to calculate the area of spherical triangles in order to estimate the sky area blocked by the PV modules for every simulated point within the field. The model is capable of simulating shading effects for fixed-tilt APV as well as one axis tracking APV, using a fixed angle or angles determined by the single axis tracking algorithms "backtracking" and "true-tracking" from pvlib python (version 0.9.3) [9].

2.2 Simulated study site

As a test case, agricultural yield prediction simulations are performed in cooperation with BayWa r.e. for a planned APV site in France. The site is located near Paris, contains crop cultivation on 18.4 ha and has a planned inter-row spacing of 13.6 m in order to allow for crop cultivation using common agricultural machinery (see *Figure 1* and *Figure 2*). Information on the historical crop rotation was kindly provided by the farmer. The modeled APV configuration consists of 50% one-in-portrait trackers (1P) and 50% two-in-portrait trackers (2P, two modules mounted side-by-side), both equipped with standard bifacial modules and east-west tracking (using the energy-optimized backtracking industry standard) to increase energy yields. The area directly below the trackers cannot be used for crop cultivation in the future, as for safety reasons, a sufficient distance between the agricultural machinery and the modules must be ensured. Consequently, these areas will be converted to green stripes (*Figure 2*). In order to estimate the effects on crop yields in advance, simulations were conducted for winter wheat (WW), spring barley (SB) and rapeseed (RS) for the years 2007 to 2020. Simulations are carried out using downscaled meteorological ICON-EU data [10]. Simulating multiple years assures statistical robustness and accounts for inter-annual variability. Light simulation results for the planned APV systems are validated with results from the bifacial radiance ray-tracing model [8].

Figure 1. *Planned BayWa r.e. project site (size 18.4 ha) in France with one-in-portrait (1P; on the left) and two-in-portrait (2P; on the right) PV trackers. (Source: BayWa r.e.)*

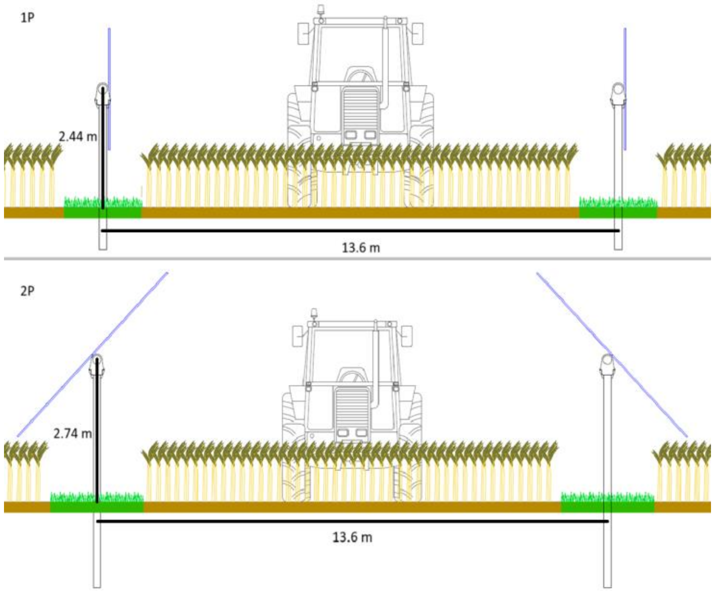

Figure 2. *Schematic illustration of the planned 1P and 2P trackers. The space between two tracker rows consists of green stripes (required to guarantee safety margins between agricultural machinery and PV trackers) and cultivated area (with size depending on agricultural machinery working widths). (Source: BayWa r.e.)*

3. Results and Discussion

Simulated light distribution patterns for the planned APV systems matched the computationally intensive ray-tracing results (see *Figure 3)* and provided modified direct and diffuse irradiances. Due to the computation-heavy nature of the ray-tracing model, its results are only available for a number of statistically selected days derived from PVGIS typical meteorological year data [11]. A comparison of the spatially averaged irradiances for both the VISTA shading model and the bifacial radiance ray-tracing model for 1P APV is shown in *Figure 3*. Discrepancies in the results can be explained by the different level of abstraction and differing assumptions between the approaches. For some hours with low global irradiance, the geometrical model predicts almost no shading in a few cases, as the sun elevation is very low and light can shine below the modules in the model (especially if the crop height is very small). At hours with higher global irradiance, the geometrical model tends to overestimate shading when compared to the ray-tracing results. This might be due to the better representation of multiple scattering processes in the ray-tracing model. However, it can be assumed that this potential slight overestimation of shading is in line with a more conservative estimate for crop yields, which is required for the planning process for the site. Overall, both models share the same trend and magnitude of global irradiance reduction due to APV shading.

For crop yields, PROMET predicted mean winter wheat yield reductions when compared to the reference without APV in the range of 4% to 19% for the modeled 1P design and ranging from 9% to 42% for the 2P design. For spring barley, mean yield reductions are ranging from 15% to 35% (1P) and from 30% to 72% (2P). Reductions in mean rapeseed yields are ranging from 6% to 25% (1P) and from 14% to 57% (2P). A crop yield pattern matching the light distribution was observed for all crops in the simulations (*Figure 4*). Yields were more heavily influenced in areas directly below the modules and were closer to reference yields in the middle between two rows of trackers. When comparing the results for 1P and 2P, there are larger areas with crop yields drastically reduced in the 2P case. This results from greater light limitation effects due to larger impacts of shading caused by the much larger PV module area when compared to 1P.

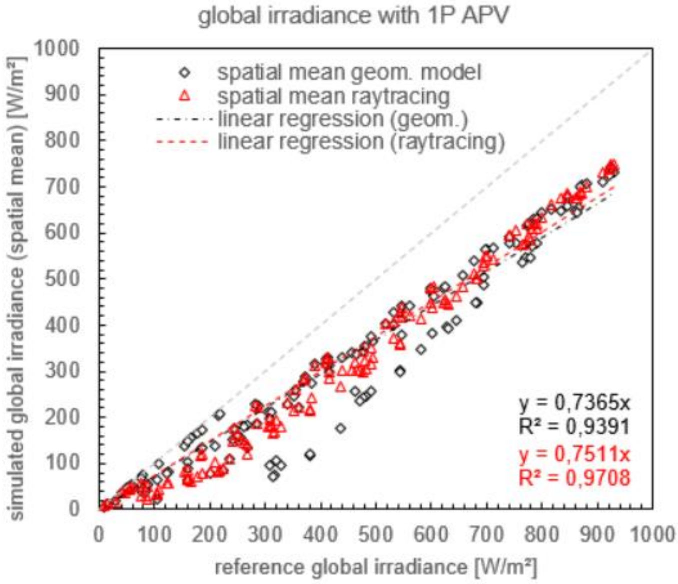

Figure 3. *Comparison of simulated global irradiance using the VISTA shading model (geom. model) and the "bifacial radiance" model (raytracing) for the test site for statistically selected typical days during the growing season. Reference is the global irradiance without any shading applied. Both models have a very similar trend and show that for the 1P system, overall the modified global irradiance is 74% (geom. model) and 75% (raytracing) when compared to the reference without PV modules.*

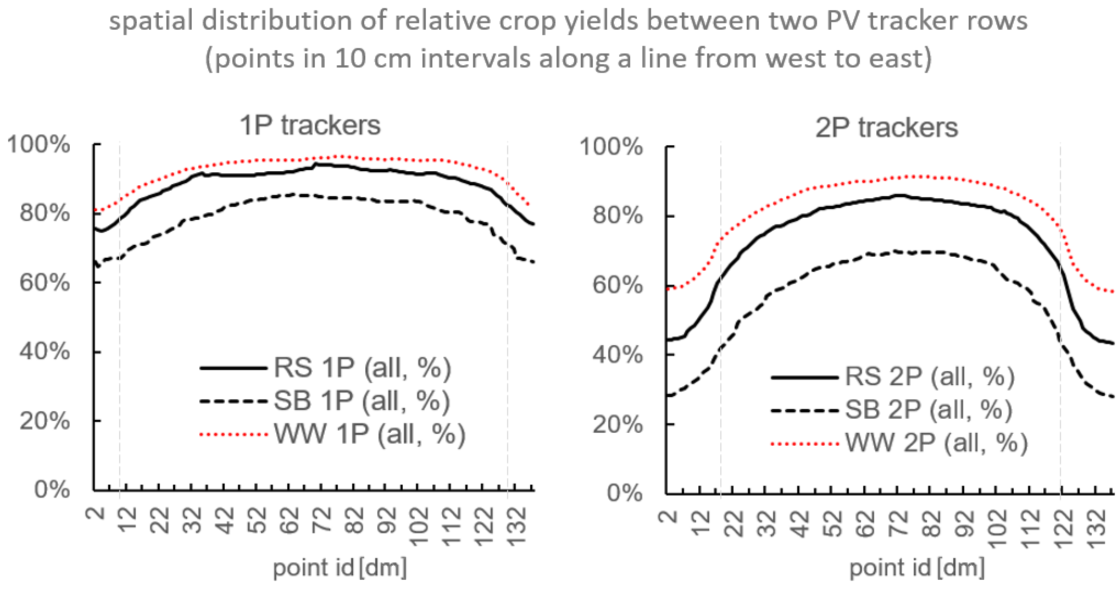

Figure 4. *Spatial distribution (west to east) of simulated relative crop yields with APV for rapeseed (RS), spring barley (SB) and winter wheat (WW). Crop yields are negatively affected by shading for all simulated crops in both the 1P and the 2P case. SB is affected the most and WW is affected the least for both APV layouts. The vertical dashed gray lines indicate the width of the planned green stripes.*

However, in both cases, the simulated crop yields in areas directly below the PV modules are less relevant to the farmer here, as they will not be used for crop cultivation in the future anyway. To maintain required safety distances for agricultural machinery, these areas will be converted to green stripes instead. Excluding these strongly shaded green stripes, spatial means of winter wheat yields were reduced by on average by 6% for the 1P design and by 16% for the 2P design (further results see *Table 1*).

Table 1. *Overall crop yield change for the remaining agricultural area of the site under construction.*

crop	single axis tracking 1P	single axis tracking 2P
winter wheat	-6%	-16%
spring barley	-20%	-39%
rapeseed	-10%	-24%

From the farmer's perspective, when looking at the crop yield for the whole area, total yield for the field is reduced by loss of agricultural area due to the PV structures and the required safety stripes. In addition, APV can generally lead to either yield reductions or increases on the remaining area caused by shading and altered microclimate. For these effects, the farmer, or in some countries (such as France) the law, defines thresholds up to which yield reductions are still within an acceptable range. The results suggest that for crop cultivation with 1P trackers, yields remain within this acceptable range (up to -10% crop yield) for winter wheat and rapeseed. For the layout with 2P trackers however, crop yields decrease more drastically for all crops.

As shown by these results, simulated crop yields are within a plausible range for the observed crops and region. It should be re-emphasized that only light limitations and their effects on crop growth and energy fluxes are included in the model so far. Other processes potentially modified by APV (e.g. altered precipitation distribution patterns or fluid dynamics) are not included in the simulations yet. When considering light limitations only, the simulated negative effects of APV on crop yield performances seem plausible, as in temperate regions, lower irradiance levels with APV might directly lead to crop growth being light-limited. As the planned site is not in operation yet, no direct validation of the results with field study data has been possible so far. However, light simulation results from the VISTA shading model could be successfully validated, using the bifacial radiance results for the statistically selected subset of days for which raytracing simulations were carried out. For light-limited sites, crop yield reduction could potentially be counteracted by using semi-transparent PV modules in the future or by developing adjusted tracking algortihms more focused on crop-specific needs. With climate change, the limiting factor could potentially shift from light availability to water availability in some regions. Therefore, further simulations using climate model data are currently in the planning stage. For the simulated site, however, cultivation with 2P trackers might not be feasible at all for some crops. In order to answer these advanced questions reliably, more research is needed.

4. Conclusion

Crop model simulations provide several key benefits, as they allow for predictions even before the APV system is installed. This also includes the possibility to look at longer time periods and different scenarios regarding APV design, management practices or even climate change. As mentioned in section 2.1, the PROMET crop model has been validated in several studies before and is in use at VISTA GmbH for yield prediction purposes on an operational basis worldwide (https://ypsilon.services). The addition of the APV shading model expands PROMET's capabilities even further. In order to support farmers and APV planners in their decisions, the presented simulation framework is capable of determining the change in crop yield under APV for different crops. A quantification of yields for different PV module layouts is possible now, as illustrated in the study. In addition, our framework helps to understand and predict the spatial patterns of light distribution affecting crop growth and assures statistical robustness of predicted average yield changes. Further potential arises with regard to modeling climate change impacts on APV and PV electricity yield simulation, which could possibly be included into the data products in the future. While the shading model and PROMET have already been tested individually, a more in-depth validation of the entire framework is planned for the near future when data for planned systems becomes available. In any case, further research is needed to fully understand and accurately describe the impact of APV on crop yields. These efforts could focus on multi-site validation, attribution of APV effects on crop growth to different altered microclimatic processes, incorporation of additional relevant processes into the models and development of adjusted management strategies for APV.

Data availability statement

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

Author contributions

F.E.S.: conceptualization, methodology, formal analysis, software, writing – original draft, visualization; H.B.: conceptualization, resources, project administration, supervision, writing – review & editing; E.B.: conceptualization, methodology, formal analysis, ray-tracing simulations, writing – review & editing; S.S.: project administration, supervision, writing – review & editing. All authors have read and agreed to the published version of the manuscript.

Competing interests

As indicated in the affiliations, the authors are employed by the respective companies.

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