AgriVoltaics World Conference 2023
PV System Technologies
https://doi.org/10.52825/agripv.v2i.996

Published: 23 May 2024

Modelling Light Interception by Rows of Tall-Growing Crops in an Agri-PV System

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Abstract. The irradiance on 3D plants, for instance for row crops, is complex to measure. Validated irradiance modelling of 3D row crops gives detailed information about the irradiance distribution on the crop canopy. It can also be applied to investigate new or changed layouts of agri-PV systems without the need to actually build them. We modelled an agri-PV system of partially transparent PV panels integrated with a soft fruit farm using the light and PV simulation package BIGEYE. The irradiance absorbed by the canopy is calculated from the difference in irradiance above and below the plants, mimicking PARbar measurements. The simulated PARbar data is in agreement with a full analysis of the modelled total irradiance on the plant row surfaces. We also show that there is a difference in the irradiance on the plant rows below the lower and higher ends of the PV panels. Finally, the irradiance along the sides is twice as high on the top third than the bottom third. The detailed information on the irradiance distribution will be compared to observed adaptations of the plants to shading.

Keywords: Agrivoltaics, Irradiance, Validation

1. Introduction

To know the effect of an agri-PV installation on crop photosynthesis, and hence crop yield, often a trial-and-error approach is used, where a particular agri-PV system is built and the effect on crop growth is measured. To correlate the yield with photosynthesis potential it is essential to know how much light is transmitted to the crop. However, in complex 3D systems such as tall-growing row crops under PV panels, the amount of irradiation on the crop is difficult to measure or predict. An alternative approach to measurements is to use validated irradiance/shading models. These can be applied to a range of layouts of an agri-PV system. The output of the model can give detailed information about the irradiance distribution on the canopy as function of the varied design parameter, and thus the expected effect on crop growth.

As a model system, an agrivoltaic system with partially transparent solar panels above rows of raspberry plants was used as installed at Agri-PV Babberich by Groenleven in the Netherlands [1]. The irradiance absorbed by the crop canopy is calculated by a full analysis of the modelled total irradiance on the plant row surfaces. As an alternative, the plant irradiance can be approximated by the difference in irradiance on two horizontal lines above and below the plants, mimicking PARbar measurements, which are used to experimentally determine the photosynthetically active radiation for crop research.

2. Methodology

In this section we describe the major components of the modelling process. The workhorse of this work is the PV simulation tool BIGEYE [2], developed by TNO to simulate the performance of PV systems, with a focus on bifacial systems. The optical model in BIGEYE dissociates the incoming global horizontal irradiance, GHI, into direct beam and circumsolar, diffuse sky-dome and horizon components. GHI data is obtained from the KNMI weather station in Deelen, the Netherlands for the two-week period 15-28 June 2022 with 10-min time resolution. BIGEYE implements a 3D view factor model to accurately handle the ground and other diffuse reflectors, for instance, the irradiance from the ground to the rear side of bifacial modules. BIGEYE has been validated and compared against other (bifacial) irradiance software [3].

A representative model of the experimental setup was created containing raspberry plants, solar panels, shading nets and PARbars above and below the plants (see Fig. 1). PARbars are rods with light sensors facing the sky and giving a total (line) irradiance value per time step.

The plant rows are represented by non-transparent, light absorbing surfaces forming a trapezium-shaped cross-section. The top and bottom surfaces are parallel and have widths of 100 and 120 cm, respectively for the top and bottom surface. The east and west facing sides of the raspberry rows are nearly vertical and stand 150 cm tall, starting at 50 cm above the ground. Plant bottom and top surfaces are, respectively, at 50 and 200 cm height.

The PV sheds, at alternating east or west direction, have 1.6×1.0 m^2 portrait-oriented modules with an estimated transparency of 40%, at 15° tilt, 250 cm above the ground.

The shading net, transparency ~60%, covers the gaps of 50 cm at the top and 80 cm at the bottom end. Alternatively, the shading net could be applied vertically, hanging from one or both ends of the PV sheds.

The PARbars are located at heights 225 and 25 cm from the ground, respectively halfway between the top of the raspberry plants and PV panels and halfway between the bottom of the plants and the ground.

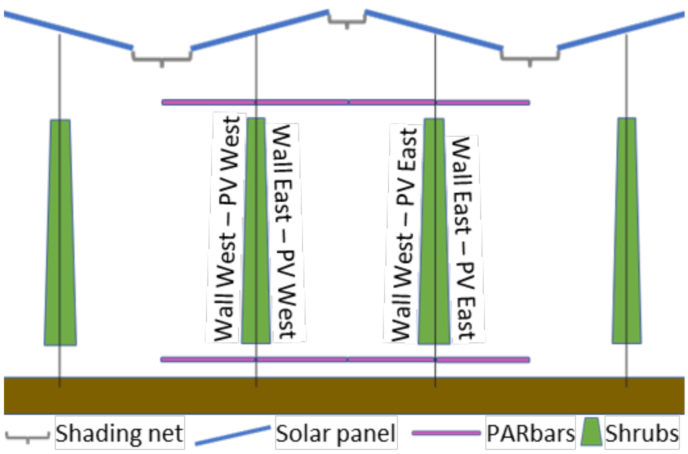

Fig. 1: Sketch of an agri-PV system as seen from the South. Dimensions and other details of the components are given in the main body of the text.

For now, the simulations are not spectrally resolved. Chlorophyll a and b absorb mostly red and blue light, hence the green colour of plant leaves. Thus the light that is scattered by leaves contains mostly wavelengths in the green range, which will not contribute significantly when reaching the next leaf. Therefore, we assume in the simulations that the plant surfaces are not scattering light.

3. Results & Discussion

We modelled the irradiance on the top and bottom PARbars. Comparison with measurements [4] gives a good agreement, but also indicates the need to include the transparency of the canopy. The difference between the top and bottom PARbars corresponds to the light intercepted by the canopy. The modelled light interception by the canopy is compared in Fig. 2 with the modelled irradiance on all surfaces of two plants, one under the west-facing, the other under an east-facing PV panel. There is a slightly higher, about 6%, amount of light intercepted by the full plant's surfaces compared to the top minus bottom PARbars.

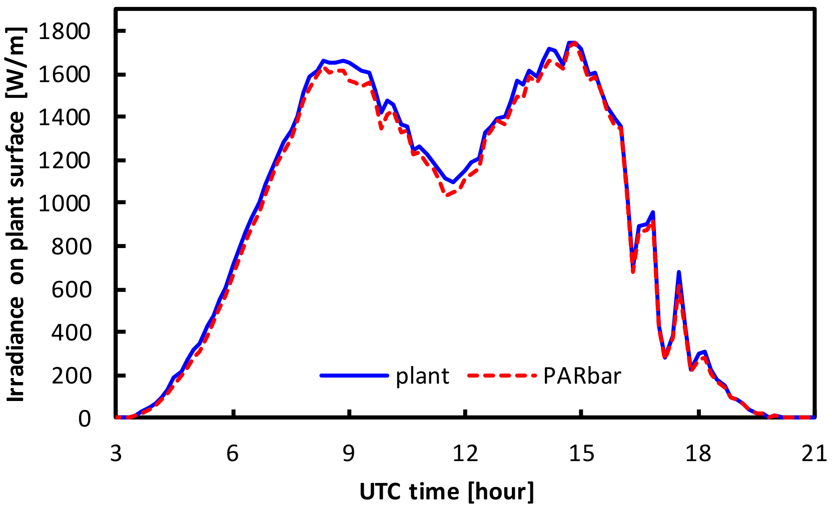

Fig. 2: Simulated irradiance on the full canopy circumference and as calculated from simulated PARbars for one sunny day, 15 June 2022.

This can be partially explained by the ground reflected light that makes up about 7% of the irradiance on the sides of the plant rows, which is, by definition, not included in the PARbar measurement and simulation. The ground reflected light however is mostly present in the middle four to six hours of the day, when the sun rays are more parallel with the rows, whereas the difference in Fig. 2 is present from early morning to the evening. Note also that grass-reflected light is mostly green light. This light can reach the raspberry plants, but will not contribute significantly towards photosynthesis.

It has been observed in the field that the lateral branches are a few centimetres longer under the lower end of the PV panels, that correspond to *Wall West – PV West* and *Wall East – PV East* in Fig. 1, compared to the branches under the higher end, *Wall East – PV West* and *Wall West – PV East*. Fig. 3 shows the simulated irradiance on these four sides of the raspberry plants, solid lines for the "lower end" walls and dashed lines for the "higher end" walls. Obviously the East walls have their irradiance peak in the morning and the West walls in the afternoon. We observe that in the morning the plant under the East-facing PV clearly has a higher irradiance compared to the plant under the West-facing PV and likewise, in the afternoon the plant under the West-facing PV has the highest irradiance. The differences in irradiance under the lower and higher ends could be responsible for the observed longer lateral branches in these regions as the plant adapts to the local environmental conditions.

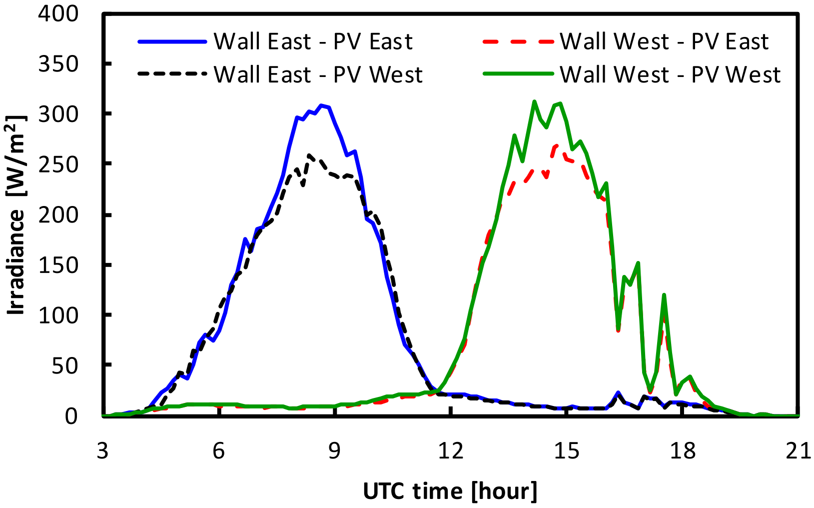

Fig. 3: Simulated irradiance, for one sunny day, 15 June 2022, on East and West sides of plant rows under West- and East-facing PV panels. The "Wall East – PV East" and "Wall West – PV West" are located under the lower ends of the PV tables.

Finally, we show how the irradiance is distributed over the height of the plants' walls in Fig. 4. Particular at the edges of the day, the top part of the plants gets significantly more light than the bottom third. At the edges of the day, that is when the sun is lower in the sky, the shade of the neighbouring plant rows is projected higher on the sides of the plant row. The higher irradiance in the afternoon, on the West side, compared to the irradiance in the morning on the East side is due to the location of the evaluated plant under PV West, see Fig. 3.

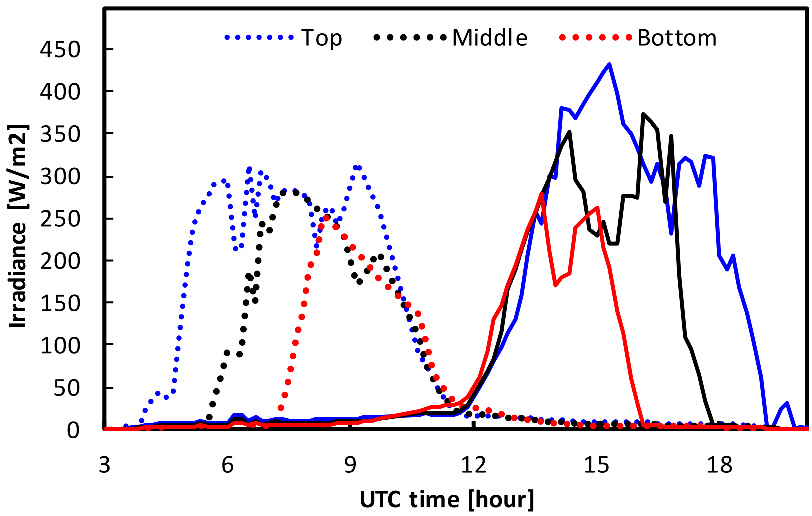

Fig. 4: Daily profile for a sunny day, 15 June 2022, of the irradiance on the bottom, middle and top thirds of the East side (dashed) and West side (solid lines) of the raspberry plants. The bottom, middle and top of the raspberry plant sides run, respectively from 50-100 cm, 100-150 cm and 150-200 cm above the ground.

4. Conclusions

We have conducted detailed simulations of the light distribution within an agri-PV system consisting of rows of raspberry plants. We showed that the PARbars above and below the plants yield very similar irradiance levels as the total irradiance on all sides of the plants.

The presence of PV panels above the raspberry plants, with and without shading nets, prevents the occurrence of high irradiance, in the 500 to 900 W/m^2 range, that would occur in a raspberry farm without PV or shading nets. Also, the time that the irradiance is at a medium level increases, likely protecting the plants against damage by too high summer irradiance.

Due to row-row shading of neighbouring plants, the bottom third of the sides of the plants get much less light than the middle and top thirds. The irradiance ratio bottom to top is roughly 2:3:4. Finally we noticed that the side of the plants located under the lower ends of the PV tables get more light than the side located under the higher ends.

To conclude, these results show the capabilities of our software package BIGEYE and that detailed analysis of light distribution can help understanding the difference in growth and ripening as are observed in agri-PV systems.

Data availability statement

The contribution is based on simulations using proprietary software. Details of the solar park design and climatic data are included in the paper. Parties with legitimate interest in the data can contact the corresponding author to discuss access.

Author contributions

AB: Methodology, Software, Writing – original draft. KC: Writing – review & editing. HH: Investigation, Writing – review & editing. BM: Writing – review & editing. FdR: Investigation, Writing – review & editing. BBVA: Formal analysis, Writing – original draft.

Competing interests

The authors declare no competing interests.

Funding

This work was partially funded by the Dutch Ministry of Economic Affairs and Climate, in the MOOI project Sunbiose (www.sunbiose.nl).

Acknowledgement

The authors thank Gerjan Wubs from Groenleven and Piet Albers, Babberich, for supporting our research on their 3 MW agri-PV demonstration site.

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