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Influence of the Albedo on Agrivoltaics Electricity Production

Cas Lavaert[1][https://orcid.org/0000-0002-5166-7441], Brecht Willockx[1][https://orcid.org/0000-0001-5564-8419], and Jan Cappelle[1][https://orcid.org/0000-0002-1526-9657]

[1] Faculty of Technology Engineering KU Leuven Gent, Belgium

Abstract. This paper aims to quantify to what extent the electricity production of two types of agrivoltaics installations (fixed vertical bifacial and horizontal single axis tracker) is affected by the installation of different ground cloths. In order to assess the potential benefits of the use of these cloths, a series of ray-tracing simulations and an extensive measurement campaign were conducted. For the fixed vertical bifacial system, the simulations showed that the white ground cloth should result in an average increase in incident irradiance of about 8% for simulated periods occurring in both March (+8.2%) and June (+7.3%). However, measurements on the vertical bifacial setup over a period of 5.5 months indicated that no measurable differences occurred between the different ground covers. Measurements on the tracker setup did show a clear measurable difference with an average increase of 25% in cumulative rear incident irradiance, also resulting in an increase in revenues, for the tracker with the white ground cloth compared to the reference tracker.

Keywords: Agrivoltaics, Albedo, Horizontal Single-Axis Tracker

1. Introduction

Agrivoltaics, a land use strategy that combines agricultural production and photovoltaic electricity generation, has gained increasing interest in both research and practical applications over the past few years [1],[2]. This approach holds great potential for addressing the challenges of food and energy security. Because farmers must respect certain buffer zones around the agrivoltaic structure to avoid collisions, agrivoltaic systems installed on arable land typically result in non-negligible land losses (unlike setups in orchards, for example) [3]. These land losses should of course be minimised as much as possible, but can usually never be completely avoided, allowing other uses of these pieces of land to be looked at.

One potential application of the unused strips of land, often discussed in literature, is to use them as flower strips [4]. The implementation of these flower strips could have a positive impact on the biodiversity of the surrounding area, and consequently on the fertility of the land [5]. While the ecological value of these flower strips is evident, their economic value is limited because the income generated from the cultivated crops is typically significantly lower than that of the electricity production from an agrivoltaic installation.

A second alternative use for the unused strips of land, under investigation in this study, is the installation of reflective ground cloths. These cloths can potentially enhance the performance of the photovoltaic installation by increasing the amount of light reflected from the ground and thus increasing electricity production [6]. This paper aims to quantify to what extent the electricity production of two types of agrivoltaic installations (fixed vertical bifacial and horizontal single axis tracker) is affected by the installation of different ground cloths. Ray-tracing simulations and an extensive measurement campaign were conducted to provide a comprehensive evaluation of the potential benefits of the use of reflective ground cloths. The details of these simulations and measurements are discussed in depth in the subsequent sections of this paper.

2. Methodology

2.1 Agrivoltaic systems

Two interspaced agrivoltaic systems were installed on the same field in Grembergen, Belgium (51.02°N, 4.12°E) as can be seen on Figure 1. Each agrivoltaic system contains three rows of PV modules with a row-to-row distance of 9 metres which is compliant with the used agricultural vehicles. Despite the fact that the optimal orientation for maximum energy yield for both setups is east-west (azimuth of 270° or 90°), the setups were installed according to the direction of the field to minimise agricultural land loss (azimuth of 240°).

Figure 1: Overview of two agrivoltaic systems in Grembergen: a fixed vertical system (left) and a horizontal single axis tracking system (right).

The first agrivoltaic system consist of three rows of vertically installed bifacial modules of the type Phono solar Half-cut PERC 455 Wp and a bifaciality factor of 0.7. Each row consists of 12 bifacial modules placed in landscape to obtain an installed capacity of 5.5 kWp per row and 16 kWp in total. Because the vertical bifacial set-up is not perfectly oriented east-west, the front of the PV modules is oriented to the south-west in order to maximise the electricity yield of the system.

The second agrivoltaic system is a horizontal single axis tracker (HSAT) with bifacial modules identical to the vertical system. Similar to the vertical arrangement, each row of the tracker consists of 12 modules placed in landscape. The tracking setup is controlled by a PLC that determines the position of the PV modules based on the position of the sun, irradiance level, windspeed, etc. Due to the mechanical limits of the tracking setup, tracking angles are limited from -50° to +50° (with 0° being horizontal).

Each row of pv modules of both tracking and vertical setup is connected to its own MPPT. Due to limited grid capacity, the total inverter power of the installation had to remain below 24 kVA. The central tracking and central vertical row were connected to a relatively large inverter in order to limit inverter clipping and obtain representative yield measurements. The other rows were connected to SMA inverters as follows:

- SMA Tripower 6.0 kVA: east and west vertical row
- SMA Tripower 8.0 kVA: central tracking and central vertical row

- SMA Tripower 8.0 kVA: east and west tracking row

2.2 Albedo manipulation

To evaluate the influence of the albedo of the buffer zones around the agrivoltaic structures on the electricity yield, this work compares three different land covers:

1. a reference with grass with an estimated albedo of 22%
2. a white ground cloth with an albedo of 75% (maximizing the albedo)
3. a black ground cloth with an albedo of 7% (minimizing the albedo)

Figure 2: Overview of the different ground covers installed underneath the agrivoltaic systems.

As can be seen on Figure 2, each row of the vertical and tracking setup is equipped with a different ground surface. The first row, with grass below it, serves as a reference row to indicate the situation that would exist without special attention for these buffer zones. The grass row is supposed to correspond with the situation with flower strips sown at the buffer zones. The other rows are equipped with a specific ground cloth (white and black) in order to cover a large albedo range. The ground cloths have a width of approximately two meters. This width corresponds to the size of the land strips that are no longer used for agriculture due to the agrivoltaic set-up.

2.3 Simulation

To validate the outcomes of the measurements, a simulation of the practical setup was built. The simulation not only enables the validation of the measured results obtained from the practical setup, but also allows for the adjustment of various parameters, including ground albedo, specific surface albedo, specific surface width, irradiance, and others. This provides the opportunity to make assumptions regarding the impact of each parameter on the final outcome. Initially, the widely-used PVsyst simulation tool was utilized. However, it was discovered that it was not feasible to modify the albedo for a specific surface, as only the overall albedo could be altered. Consequently, another raytracing program, Bifacial Radiance, was selected to perform the desired simulations [7].

Using bifacial radiance, a scene is created with the specific ground surfaces and appropriate module configurations. Then, the support structure of the solar panels are added to arrive at the result shown in Figure 3. Subsequently, specific points on the modules were chosen as sensor points to evaluate the incident irradiance on the front and the backside of the modules. These sensor points were chosen to match the placement of the sensors on the actual setup. Finally, EPW weather files were imported to simulate two representative days from the measurement period.

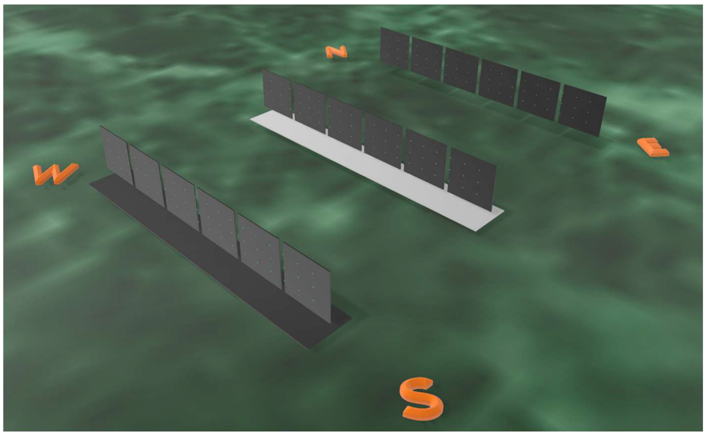

Figure 3: Visualisation of fixed vertical agrivoltaic system in the simulation environment

2.4 Measurement setup

In order to assess the impact of diverse ground covers, which lead to distinct albedo levels, on the electricity generation output, a number of sensors were used. Primarily, data from the SMA inverters are utilized. These inverters enable measurement of the DC power of each PV-string and the total AC power per inverter. However, the measurement accuracy of these inverters is relatively low, and as such, the resulting data are only used as a reference point to identify general trends, rather than for precise comparisons [8].

With the measuring of pure electrical quantities one risks to falsely identify influences of structure shading and module contamination as variations caused by albedo. To circumvent this, multiple reference irradiance cells (IMT solar Si reference cell, ±1 W/m²) measure the impact of diverse albedo surfaces on electricity generation. For the fixed vertical bifacial configuration, two reference cells (east and west) were installed at a height of 1.5 m (midpoint between the two rows of modules) for each row. This height was selected to measure the average effect of the different ground covers.

In the case of the horizontal single-axis tracker, only the central tracker was equipped with two reference cells, one at the front and one at the back of the module. Given that the three trackers are oriented identically (controlled by the same tracking algorithm), it was assumed that the two outermost trackers would receive an almost equal amount of sunlight at the front of the module as the central tracker. However, the two outer trackers were equipped with a reference cell at the back of the solar module because the back of the module primarily captures reflected light and is therefore highly influenced by the ground surface albedo.

In addition to the reference irradiance sensors, a range of meteorological sensors were installed to measure ambient temperature, wind speed, Global Horizontal Irradiance (GHI), and other parameters. All of these sensors were integrated into a Modbus data acquisition system, allowing for more than 200 sensors to be read using only four wires (24V+, 24V-, and two data wires). The data from all of these sensors was then collected by a microcomputer at a resolution of 1 minute and transmitted to a cloud-based database for storage and analysis.

The reference cells and the different ground cloths were installed in mid-December resulting in a measurement period of about 3.5 months, from 12/12/2022 until 29/05/2023.

3. Results

3.1 Simulation

Due to the computationally complex and time intensive nature of the raytracing simulations, investigations were only conducted for the fixed vertical bifacial setup and limited to two specific days. Simulations were not conducted for the tracking setup in this study due to its primary focus on the vertical bifacial setup. The cumulative irradiance for the central vertical was computed for a sunny day in March (Figure 4, left) and a slightly cloudy day in June (Figure 4, right). In this context, simulations were performed for a reference ground surface (grass) and a white ground surface (white ground cloth) respectively.

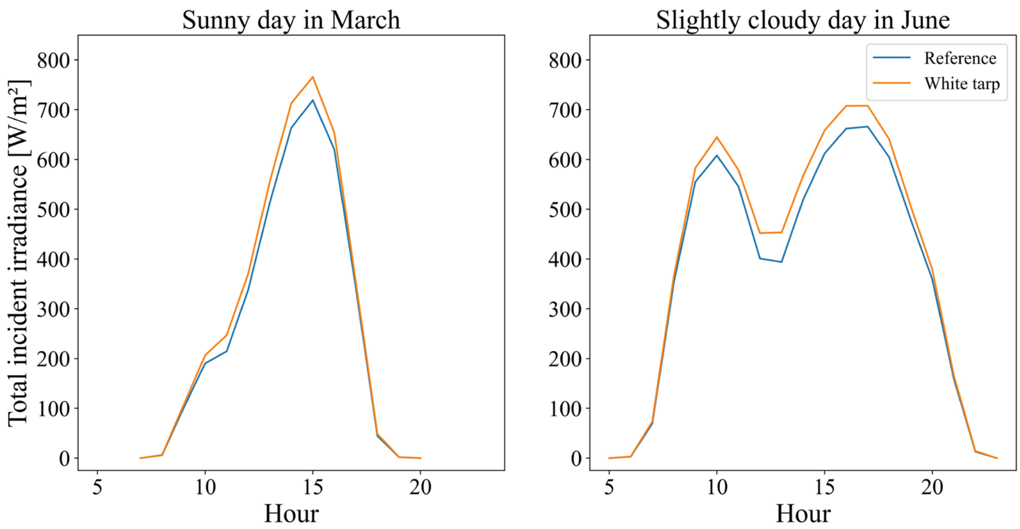

Figure 4: Simulation results for the central row of the fixed vertical system.

Based on the results of simulations, it has been determined that the implementation of white reflective ground cloths yields a notable rise in incident irradiance, averaging at approximately 8% for simulated periods occurring in both March (+8.2%) and June (+7.3%). Nonetheless, given the relative low solar elevation angles in March, the impact of these reflective materials on incident irradiance before the noon hours is rather minimal, as illustrated in Figure 4.

3.2 Vertical Bifacial Measurements

Figure 5 shows the measured total incident irradiance for the three rows with the vertical bifacial modules with three different ground covers. The presented measurements were obtained on a sunny day during the month of March and May. Consequently, the observed data serve as a reliable point of reference for comparison with the simulated results presented in Figure 4, which were simulated with comparable weather conditions.

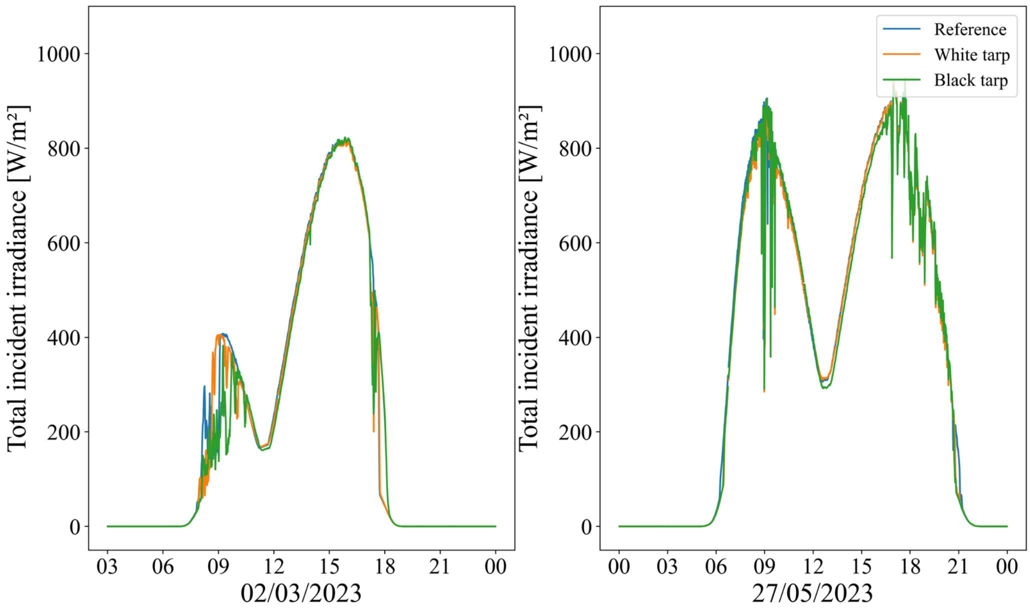

Figure 5: Total measured incident irradiance for the fixed vertical setup.

Figure 5 shows that no measurable differences can be observed in incident irradiance between the three different rows with three different ground covers. In addition, Figure 5 (left) also shows that, in the morning, distinct irregular shading occurs. This shading can be explained by a row of trees not far from the PV plant.

Finally, Figure 6 shows the total cumulative irradiance over the measured period and the relative difference with the reference row. Once again, it can be observed from the data presented in this figure that there are no distinguishable differences between the various rows of bifacial photovoltaic modules with other ground surface types. The small differences that are observed can be explained by row-to-row shading and the shade of the surrounding trees.

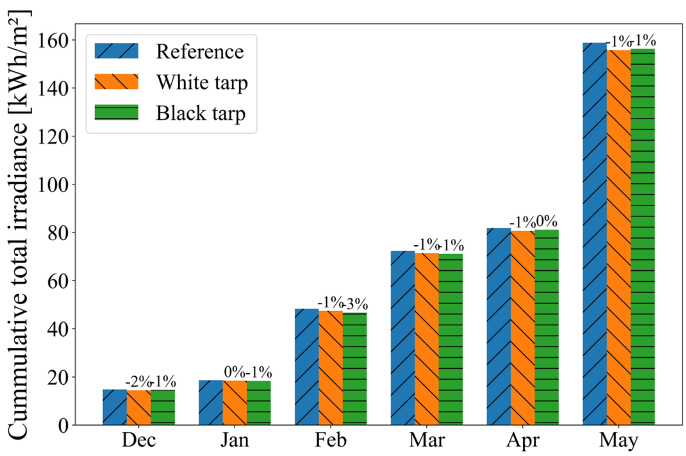

Figure 6: Measured cumulative total irradiance for the fixed vertical setup.

Due to the fact that these measurement results show no discernible differences between the three different ground covers for the fixed vertical system, no further analyses were performed on this setup, but instead, the main focus was shifted to the results of the HSAT.

3.3 Horizontal Single Axis Tracker Measurements

In contradiction to the findings from the fixed vertical configuration, the collected measurement data from the horizontal single-axis tracker (HSAT) configuration does result in clear differences between the different ground covers. Figure 7 shows both rear incident irradiance and optical bifacial gain for two days in February (a cloudy and sunny day).

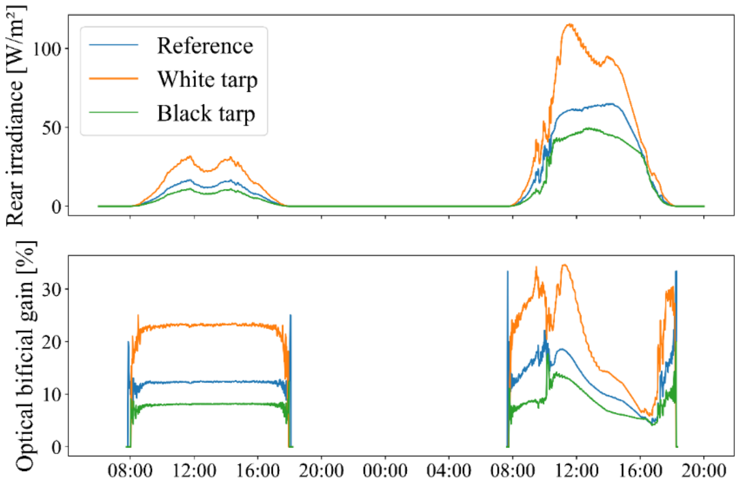

Figure 7: Irradiance measurement data for the HSAT setup on 12-13/02/2023.

The first day shown on Figure 7 is a cloudy day resulting in little direct light and a lot of diffuse light. The absence of much direct light leads to the optical bifacial gain (bottom graph) being almost constant. It is also clear that the white fabric and black fabric respectively cause an increase and decrease in the rear incident irradiance and consequently in the optical bifacial gain. The second day is a more sunny day resulting in higher absolute values for the rear incident irradiance compared to the cloudy day. Finally, the optical bifacial gain is also highly variable on this second day. This illustrates that the effect of the reflective ground cloths, on a sunny day with a lot of direct light, is highly dependent on the position of the sun.

Next, the influence of the different ground covers on the rear incident irradiance over the measured period is shown on Figure 8. This figure shows that, from December to March, the incident irradiance on the rear of the tracker monthly increases by about 28% compared for the row with the white ground cloth compared to the reference tracker. In turn, the black ground cloth causes a decrease of approximately 28% in cumulative rear incident irradiance compared to the reference tracker during the same period.

However, the months April and May show different results. The increase in the incident irradiance on the rear of the tracker with the white ground cloth decreases to only +18% and +14%, respectively. A similar trend can also be seen for the tracker with the black ground cloth. This decreasing influence of the reflective ground cloth can be explained by the fact that crops, sown between the agrivoltaic rows, grow and thus start shading the reflective ground cloths partially.

Finally, it is important to acknowledge that the relatively low absolute values of irradiance observed in April can be explained by missing data. Nevertheless, the relative data still provides a representative depiction of the situation.

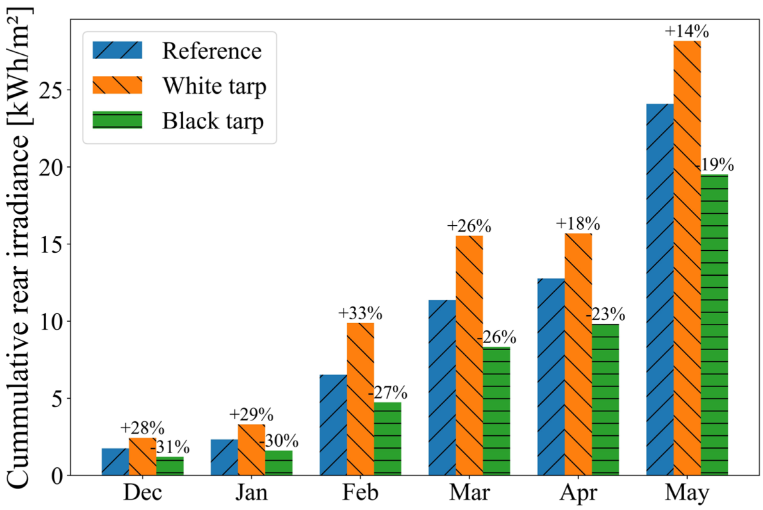

Figure 8: Measured cumulative total irradiance for the HSAT setup.

The measured irradiance on the back of the modules, combined with the measured irradiance on the front of the modules, is then converted to a DC energy yield, using the PVwatts model in python [9]. According to this calculation the DC energy yield, of the tracker with the white ground cloth, would increase with 2.4% over the measured period compared to the reference tracker. The energy yield of the tracker with the black ground cloth would decrease with 2.0% compared to the reference tracker.

4. Discussion

From the results shown in Figure 6 and Figure 8 it can be concluded that the white ground cloth has no measurable influence on the electricity production of the vertical bifacial setup during the measured period, but does result in a small increase in electricity production for the tracker setup. However, the additional electricity output and associated revenues are very limited which, taking into account the CAPEX and OPEX for the installation and maintenance of the reflective ground cloths, may not make it economically interesting to install them.

On top of that is the fact that the dimensions of the ground cloths used in this study are unrealistic for large-scale agrivoltaic installations. In this study, ground cloths of 2 meters wide were used (1 m on each side of the PV modules) due to the fact that these were the dimensions of the buffer zones in this agrivoltaic test setup. In large-scale agrivoltaic installations, buffer zones are usually limited to 0.5 m on each side of the PV modules resulting in a reflective surface with a maximum width of 1m. Thus, the increase in electricity production in actual installations will be even lower than presented in this study.

Finally, it should be noted that the simulated DC yield of the tracker setup is an overestimate of the actual measured DC yield as shown on Figure 9. Possible causes of this lower measured DC electricity yield are:

- Shade of the support structure (torque tube, aluminium profiles, etc.) on the back of the modules.
- Heavy soiling of the modules due to the agricultural environment.
- Partial shading of modules, not measured by the centrally located reference irradiance sensor.
- Clipping of the inverter.
- Limited accuracy of SMA inverter measurements.

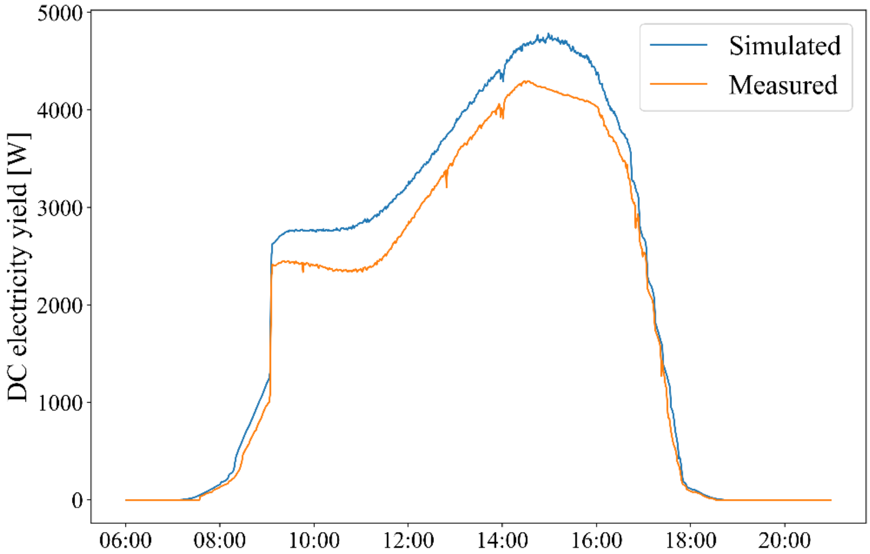

Figure 9: Comparison between measured and simulated DC electricity yield for the central tracker with the white ground cloth.

5. Conclusion

In this study, the influence of three different types of land covers on the electricity production of two types of agrivoltaic installations was assessed. Simulations suggested that for the vertical bifacial setup, the white ground cloth should bring an average increase in incident irradiance of about 8%. However, measurements on the practical setup over a period of about 5.5 months indicated that no measurable differences occurred between the different ground covers.

Measurements on the tracker setup did show a clear measurable difference with an average increase of 25% in cumulative rear incident irradiance for the tracker with the white ground cloth compared to the reference tracker. In turn, the tracker with the black ground cloth showed an average decrease of 26% in cumulative rear incident irradiance compared to the reference tracker.

Despite the increase in electricity produced by the installation of white ground cloth at the tracker installation, this study concludes that it is not interesting to integrate these reflective ground cloths into an actual agrivoltaic installation. This is because the additional produced electricity and associated revenues do not outweigh the additional CAPEX and OPEX caused by these reflective ground cloths.

Data availability statement

The data will be made available by the author on request.

Author contributions

Cas Lavaert: Methodology, Software, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing.

Brecht Willockx: Methodology, Software.

Jan Cappelle: Formal analysis, Supervision, Funding acquisition.

Competing interests

The authors declare no competing interests.

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