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Validation of Vertical Bifacial Agrivoltaic and Other Systems Modelling

Effect of Dynamic Albedo on Irradiance and Power Output Estimations

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Abstract. In agrivoltaic systems combining solar photovoltaic and agricultural activities, ground albedo is mainly characterized by the crop and its seasonal variations. This study examines the effects of using fixed, satellite-derived, and hourly measured albedo on the performance of a vertical bifacial system and a 1-axis tracking system using a bifacial photovoltaic model (AgriOptiCE®). The model is developed with Matlab® and partially based on the open-source package *pvlib*. AgriOptiCE® is firstly validated by comparing estimated front and rear irradiances with on-site measurements for specific periods from a 1-axis tracker site in Golden, USA and a vertical agrivoltaic system in Västerås, Sweden. Furthermore, photovoltaic system power output estimations using AgriOptiCE® are also validated for the vertical agrivoltaic system and the conventional ground-mounted fixed-tilt system at the same location. The validations demonstrate the high accuracy of the proposed model in estimating front and rear irradiances and power output, obtaining R^2 > 0.85 for all the studied cases. The study results indicate that measured albedo provides the highest accuracy, while satellite-derived albedo has poorer results due to the broader spatial, temporal, and spectral resolution. Fixed albedo is not recommended for yearly assessment of bifacial PV systems because it cannot account for snow events and daily variations, resulting in lower overall accuracy.

Keywords: Agrivoltaics, Albedo, AgriOptiCE, Modelling and Simulation, Bifacial PV

1. Introduction

Conventional ground-mounted (GM) bifacial photovoltaic (PV) systems typically receive a major contribution of direct light on the front side of the PV module and reflected light on the rear side throughout the day [1]. The amount of reflected radiation depends on the system design and ground albedo, which varies seasonally and daily [2]. Despite this variability, albedo is often considered as a fixed value throughout the year due to a lack of monitoring data [3]. There is in general a lack of studies on the impact on the power output when simulating with a dynamic albedo compared to a fixed one [4]. In agrivoltaic (AV) systems, ground albedo varies mainly due to the crop and its seasonal changes. Therefore, using a fixed albedo value to estimate the annual electricity yield in an AV system will most probably lead to errors.

The study uses the AgriOptiCE® model to estimate both irradiances and power output of the bifacial PV systems. Validation of the model is initially performed by comparing front and rear irradiances estimations with real measurements from a horizontal 1-axis (1-AX) East-West tracker system in Golden, USA and a vertical agrivoltaic (VAV) East-West system in Västerås, Sweden. The validation is then extended to power output estimations compared to measured power from the VAV system and for the conventional South-oriented GM fixed-tilt system in

Sweden. Lastly, this study evaluates the effects of using fixed, satellite-derived (daily resolution) and 15-min or 5-min in-situ measured albedo values on the front and rear irradiance predictions of the 1-AX system and on the power output estimations of the VAV.

The paper is structured as follows. Section 2 describes the PV systems analysed, including their location and weather data. A description of the AgriOptiCE® modelling tool is also provided. Section 3 presents the validation results for both irradiances and power output for the specific studied periods. The contribution of direct, diffuse, and reflected irradiance components for the different PV systems analysed is also presented. Finally, the results of using fixed, satellite-derived, and dynamic albedo on both irradiance and power output estimations are shown. Section 4 concludes the work and provides an overview of future research directions.

2. Methods

2.1 PV Systems Site Characteristics and Data

This study considers three different bifacial PV systems, as shown in Figure 1. The first system is a VAV bifacial system, consisting of 3 rows, each with a length of 18 meters, a pitch of 10 meters and a clearance height of 0.80 m. This system has an installed capacity of 22.8 kW_p and uses Jolywood modules (JW-D72N-380). The second system is a GM fixed tilt bifacial PV system with a tilt angle of 30 degrees, consisting of two rows, each with a length of 8.5 meters, a pitch of 9 meters and a clearance height of 0.77 m. This system has an installed capacity of 11.8 kW_p and uses Longi modules (LR4-60HBD-370M). Both the AV and GM systems are in Västerås, Sweden (59.55°N, 16.76°E). The third system is a 1-AX tracking bifacial PV system, consisting of ten rows with a ground cover ratio of 0.35 and an installed capacity of 75 kW_p. This system is in Golden, USA (39.74°N, 105.17°W) and belongs to the National Renewable Energy Laboratory (NREL), further system parameters can be found in [5].

Figure 1. Photographs of the vertical AV system (left), GM fixed-tilt system (middle) near Västerås, Sweden and the 1-axis tracking system (right) in Golden, USA [5].

On-site data collection is performed for the Swedish location using a Lufft WS600-UMB Smart Weather Sensor to measure ambient temperature and wind speed. Delta-T SPN1 Sunshine Pyranometer is used to measure global and diffuse horizontal irradiances, and Solar-Log Sensor Box Professional Plus is used to measure east and west plane-of-array (POA) irradiances located in the middle row, 4th pole from the northernmost one, and mid-height away from edge effects. Apogee SP-710-SS Albedometer is used to collect albedo data. The data is logged at one-minute intervals and underwent quality checks, including filters and visual inspections, to eliminate outliers and missing data. Power inverter data for the vertical bifacial system and the GM system are logged every 5-min. For the site in Golden, USA, 15-min data are retrieved from Ayala & Deline [5]. Monitored weather parameters correspond to the NREL Solar Radiation Research Laboratory (SRRL) station and front and rear irradiances for the 1-AX tracking PV system correspond to the 9th row POA irradiances. Daily satellite-derived albedo data is extracted from MODIS MCD43A4 v006 [6] and linearly interpolated for the desired resolution.

2.2 AgriOptiCE®

The bifacial PV model proposed in this study is a continuation of the model developed by Campana et al. [7]. A flowchart illustrating the AgriOptiCE® modelling framework is presented in Figure 2. This study focuses on applying and validating the part of the framework concerning PV electricity production modelling (depicted by the orange boxes). The bifacial PV model is developed using Matlab® and incorporates certain modules from the open-source library *pvlib* [8]. The model has the capability to simulate PV performance at any desired time resolution based on the input data. It should be noted that the model is still undergoing development, and factors such as spectral mismatch, soiling, edge effects, and mounting structure losses are yet to be included. The PV system geometry is currently simplified, excluding panel spacing and mounting structures. Shading losses between PV module rows are calculated geometrically using a similar approach as described in Zainali et al. [9], and the ground-reflected irradiance is determined through a 2D view factor approach.

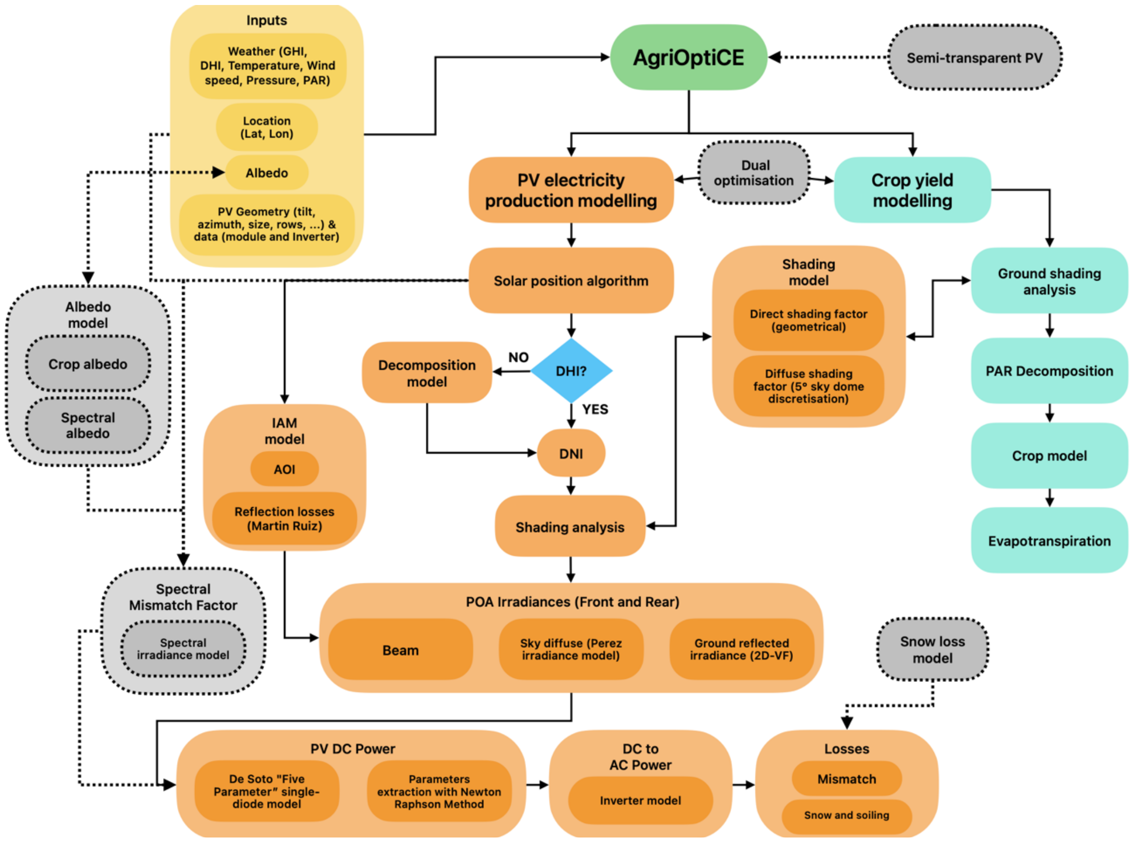

Figure 2. Flowchart of the modelling framework. The grey boxes and dashed lines indicate modules under development and to be implemented in future versions.

3. Results and Discussion

3.1 Model validation: irradiances and power output

The validation results for estimating the front and rear irradiances of the 1-AX tracking system and the east and west irradiances of the vertical system are tabulated in Table 1. The AgriOptiCE® model demonstrates high accuracy for both systems with R^2 values exceeding 0.85. However, deviations occur due to the absence of specific sub-modules in the model as mentioned in Section 2.2. Increased deviations are particularly noticeable on the front side and, to a greater extent, on the rear side of the 1-AX tracking system. These could be attributed to the placement of the POA irradiances measurements not perfectly located at the middle of the row, making them susceptible to edge effects. The current simulation, with its simplified geometry, does not account for edge effects. Nevertheless, the model accurately estimates POA irradiances when edge effects have less impact, as observed for the VAV system ($R^2 \geq 0.93$), where the POA irradiances are measured at mid-height and away from the edges. It should be noted that the shorter analysis period for the VAV system was due to the unavailability of recorded data. The 1-AX tracking system is analyzed with 15-minute resolution data, while the vertical system is analyzed with 5-minute resolution data, to capture the variable changes in sky conditions and the sun's azimuth and elevation angles.

Table 1. Results of the validation comparing the simulated and the measured POA irradiances for both the 1-AX tracking system (Golden, USA) and VAV system (Västerås, Sweden). Analysis period: Jan – Dec 2020 (1-AX, n° points: 32,422), Jul – Aug 2022 and Feb – Mar 2023 (VAV, n° points: 26,723).

	R^2	MAE (W/m²)	RMSE (W/m²)
Front side (1-AX, 15-min)	0.88	47.17	123.20
Rear side (1-AX, 15-min)	0.85	9.36	18.23
East side (VAV, 5-min)	0.93	16.97	50.39
West side (VAV, 5-min)	0.95	12.94	39.34

Table 2 displays the validation results for the simulated power output of the VAV system and the GM fixed-tilt system using instantaneous 5-min and hourly data for a period of approximately 8 months, limited to data availability. The simulated power output exhibits high accuracy compared to real power inverter data, with R^2 values above 0.9 and RMSE values below 1.5 kW for all cases. The difference in total energy conversion between the two temporal resolutions is 16.82 kWh for the VAV in the studied period, indicating that the hourly resolution results in a slight overestimation of 0.19% compared to the 5-min resolution.

Table 2. Results of the validation comparing the simulated AC power and the measured AC power from the inverter for both the vertical AV system and GM fixed-tilt system in Västerås, Sweden. Analysis period: Jun 2022 – Mar 2023. Note: the vertical AV system has fewer data points due to inverter switch-offs and clipping during certain periods.

	Number of data points	R^2	MAE (kW)	RMSE (kW)
VAV (5-min)	33,798	0.91	0.59	1.38
VAV (1-h)	2,722	0.93	0.54	1.26
GM (5-min)	44,852	0.93	0.29	0.77
GM (1-h)	3,602	0.93	0.30	0.76

Figure 3 (left) presents a comparison of the simulated and measured power for specific days, demonstrating the high accuracy of the proposed model for clear-sky and cloudy conditions. Nonetheless, slight overestimations of the simulated power are evident, as observed in the average daily specific yield during the studied months (Figure 3, right). These overestimations can be attributed to the challenges of accounting for all system losses, which are not yet fully incorporated into the model.

It is evident that during snow conditions, the prediction errors are significant, particularly for the ground-mounted system, as depicted in Figure 4 (left). This is because the snow loss model is not yet integrated into the AgriOptiCE® model as mentioned earlier. The same trend is observable in the average daily specific yield (Figure 4, right), especially for the period of Feb – Mar 23, where there are more sun hours. In these cases, the overestimation of simulated yield is greater because due to the presence of snow events, which increases the albedo and thus the simulated production. However, the front side of the panels could still be covered by snow, as seen in Figure 4 (center).

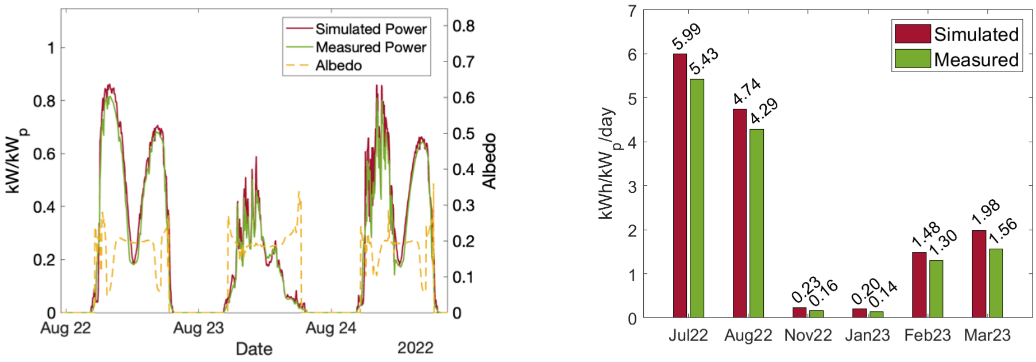

Figure 3. Left: Comparison between simulated and real measured AC power for three days using 5-min data for the VAV system in Västerås, Sweden. Measured albedo is depicted in a dashed line. Right: Comparison of simulated and measured average daily specific yield per month for the VAV system. Note that certain months may be omitted or may not include data for all days due to data quality issues or missing data.

Figure 4. Left: Comparison between simulated and real measured AC power during a period with snowfall using 5-min data for the GM system in Västerås, Sweden. Center: Photograph of the GM system in Västerås covered with snow. Right: Comparison of simulated and measured average daily specific yield per month for the GM system. Note that certain months may be omitted or may not include data for all days due to data quality issues or missing data.

3.2 Direct, diffuse and reflected irradiances contribution

Figure 5 (upper row) illustrates the contribution of the different irradiances components (direct, diffuse, and reflected) to the front and rear sides of the studied bifacial PV systems for a day without snow and a day with snow. The ground conditions refer to ley grass or natural field for the representative day without snow. The rear side of the GM and 1-AX tracking systems receive a majority of the ground-reflected irradiance, which is strongly influenced by the ground albedo conditions. In contrast, both the east and west sides receive a similar amount of ground-reflected irradiance for the VAV system, with a higher contribution of this component in snowy conditions. The daily plots presented in the lower row of Figure 5 correspond to the selected days used to generate the bar plots. It is worth noting that, in the GM and 1-AX systems, the rear side irradiance is higher during snowy conditions than days without snow, even though the global horizontal irradiance (GHI) is lower on snowy days. These observations highlight the significant role of ground albedo on the rear side irradiance of bifacial PV systems.

3.3 Effect of measured, satellite-derived, and fixed albedo values on irradiance and power output estimations

Figure 6 illustrates the rear side irradiances of the 1-AX system in the USA, simulated using AgriOptiCE® with measured 15-min, satellite-derived, and fixed albedo values, following the analysis approach of Nygren & Sundström [4]. The rear side irradiance is underestimated when a fixed albedo of 0.26 (the yearly average of the site [5]) is used, indicating its inability to represent snow events. Employing satellite-derived albedo yielded improved results compared to fixed albedo (R^2 of 0.58 > 0.42). However, the lower accuracy of daily temporal resolution and spatial resolution (pixel size ~500m [6]) limits its performance compared to the 15-min in-situ measurements (R^2 of 0.75). The impact of using measured, satellite-derived, or fixed albedo on the front side of the 1-AX system is minimal, as the ground-reflected component has less influence (as observed in Figure 5). In the VAV system, where the contribution of ground-reflected irradiance is not substantial (10% to 30% of the total irradiance in Figure 5) and is evenly balanced between the east and west sides, the effect of different albedo resolutions is not pronounced. However, the results still indicate better estimations using in-situ measurements than a fixed albedo value (Table 3).

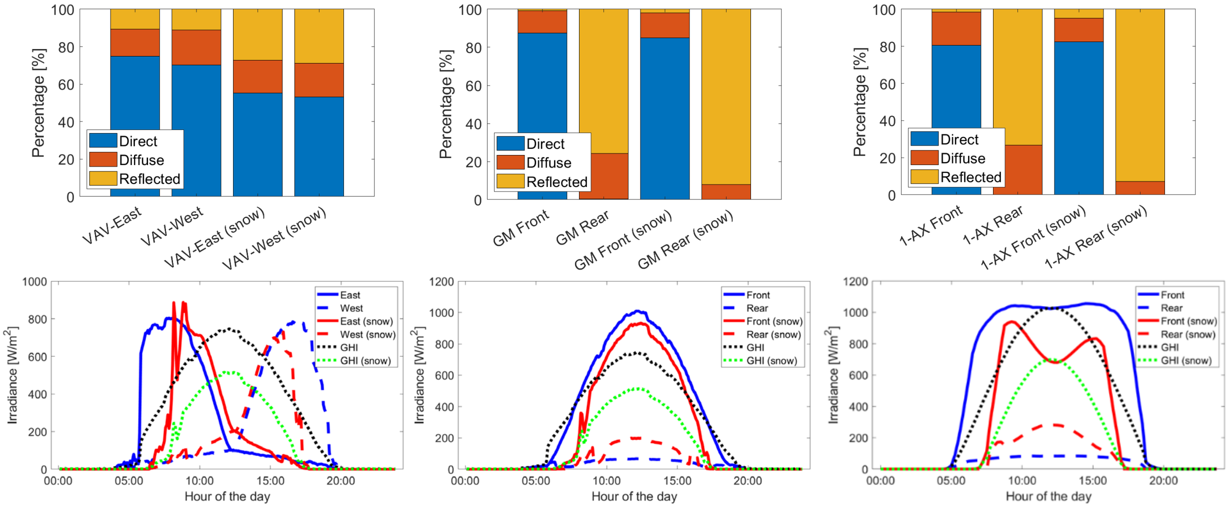

Figure 5. Upper row: Contribution of irradiance components to the front and rear side of the studied bifacial PV systems. Lower row: 5-min (VAV and GM) and 15-min (1-AX) total irradiance received for the front and rear sides of the studied bifacial PV systems and GHI for the analysed days. Plotted days: 12th Aug 2022 and 12th Mar 2023 (snow) for Västerås, Sweden; 1st July 2020 and 11th Feb 2020 (snow) for Golden, USA. Note that slight asymmetry is observed in both the VAV and GM systems due to a 6° clockwise deviation from their designed orientation, i.e., E/W and S, respectively.

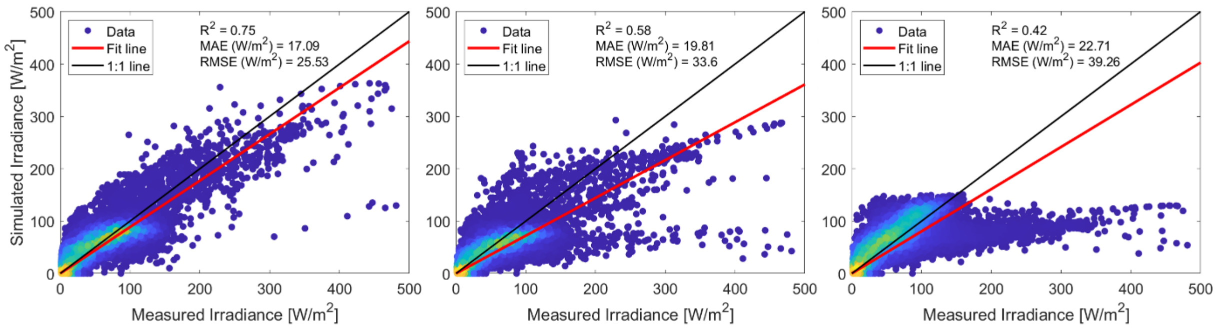

Figure 6. Simulated rear irradiance (Jan-Dec 2020) using AgriOptiCE® compared to the measured irradiance for the 1-axis tracking system located in Golden, USA. Left: with measured 15-min albedo from NREL Solar Radiation Research Laboratory station. Center: with MODIS daily satellite-derived albedo linearly interpolated to 15-min. Right: with a fixed albedo of 0.26. Number of data points: 16,474. Points with solar elevation angles ≤ 0 are removed. Lighter colours indicate more points in the vicinity.

The discrepancy resulting from using in-situ albedo measurements, satellite-derived albedo values, or a fixed albedo for estimating POA irradiances is evident, particularly for the side that receives a significant contribution from the ground-reflected component. An incorrect estimation of POA irradiance directly affects the prediction of power output for the bifacial PV system. The findings highlight the limitation of using a fixed albedo value throughout the year in annual simulations, a common assumption in such assessments. Ground conditions, particularly in snowy environments, significantly impact the albedo value. Therefore, higher albedo resolution, such as daily, monthly, or seasonal, should be considered. If ground albedo measurements are available, they should be utilized. Another approach is to estimate daily, monthly, or seasonal averages based on one year of ground albedo observations or develop a site-adaptation model. This model could then be applied to similar latitudes, environments, and crops. However, it is important to note that ground albedo values vary with different crops and their growth stages. Thus, if a different crop than the one measured is being planted, new measurements would be necessary. The research group is currently investigating the albedo of different crops to gain a better understanding and prediction of albedo in AV systems. Additionally, the results indicate that if ground albedo is not monitored, a more suitable option for estimating PV system performance than using a fixed albedo value is to utilize satellite-derived albedo, which is available worldwide. Alternatively, combining ground albedo measurements with satellite-derived albedo can be considered, although this is beyond the scope of the current work.

Table 3. Results between simulated and measured power (Jun 2022 – Mar 2023) for the VAV system near Västerås, Sweden. The fixed albedo value of 0.22, which is the average value for the site during the analysed period is used. Number of data points: 17,179. Points with solar elevation angles ≤ 0 are removed.

Albedo	**R^2**	**MAE (kW)**	**RMSE (kW)**
5-min measured	0.87	1.07	1.88
Satellite-derived	0.87	1.06	1.89
Fixed 0.22	0.86	1.17	1.94

4. Conclusion and future work

This study focused on the impact of ground albedo on ground-reflected irradiance and its influence on the performance of different bifacial PV system designs. In AV systems, ground albedo varies as crops undergo visual changes during their growing stages, emphasizing the need for variable albedo value when evaluating PV power output. While in-situ albedo measurements provide the most accurate results, satellite-derived albedo can serve as an alternative solution when in-situ data is unavailable. However, attention must be given to the temporal and spatial resolutions. Fixed albedo values throughout the year are not recommended as they fail to accurately represent changes in ground albedo conditions resulting from growing crops or snow events.

The AgriOptiCE® PV power output modelling tool has been validated with high accuracy for a vertical bifacial AV system and a GM fixed-tilt bifacial system (R^2 above 0.91, RMSE below 1.38 kW and MBE below 0.59 kW). Moving forward, the tool will be enhanced by incorporating additional features that account for other system designs and losses, further improving the model's accuracy. Extending data collection for longer periods will enable the model to be validated on an annual basis, which annual yield calculations are more relevant in the PV industry. The proposed modelling tool will be compared with existing software (e.g., PVSyst, SAM) and ray-tracing based tools (e.g., bifacial_radiance) to evaluate power output estimation. Additionally, the integrated model AgriOptiCE®, which is capable of estimating crop yields, will be validated through field experiments. Lastly, a better understanding of albedo variability under AV systems is necessary and the effects of snow albedo on different bifacial systems are currently under investigation.

Data availability statement

The data that supports the findings of this study are available from the corresponding author, Silvia Ma Lu, upon reasonable request.

Author contributions

Silvia Ma Lu: Conceptualization, Methodology, Data curation, Validation, Formal analysis, Writing – Original Draft, Writing – Review & Editing; **Sebastian Zainali**: Writing – Review & Editing; **Elin Sundström**: Writing – Review & Editing; **Anton Nygren**: Writing – Review & Editing; **Bengt Stridh**: Writing – Review & Editing; **Anders Avelin**: Writing – Review & Editing; **Pietro Elia Campana**: Conceptualization, Funding acquisition, Writing – Review & Editing

Competing interests

The authors declare no competing interests.

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