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Vertical bifacial PV systems: irradiance modeling and performance analysis of a lightweight system for flat roofs

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Abstract. Vertical bifacial photovoltaic (PV) systems are gaining interest as they can enable deployment of PV in locations with grid or area limitations. Over Easy Solar has developed a lightweight design for vertical bifacial systems for flat roofs employing small modules with the height of one cell. To model the expected output of these type of systems can, however, be challenging, as it is uncertain if conventional models will give accurate results for vertical bifacial PV. The irradiance conditions are different, and there can be other loss or gain mechanisms that are prominent in these types of systems compared to more conventional PV systems. In this study we assess the use of regular transposition modeling for plane of array irradiance modeling for vertical bifacial PV, and we evaluate the performance of Over Easy Solar pilot installations in Norway to identify prominent loss mechanisms. The results are relevant for most vertical bifacial systems. With regular transposition modeling plane of array irradiance is overestimated by less than 1%, but we find that accuracy of albedo input and choice of sky diffuse model impact modeling accuracy. Irradiance losses such as shading are not considered in the modeling. We calculate a median heat transfer coefficient of 55 W/m^2K, indicating high heat transfer and low thermal losses. High annual plane-of-array insolation, module bifaciality, interrow shading, reflection losses caused by high angle of incidence of the direct irradiance, and snow also have significant impact on the overall performance.

Keywords: Vertical bifacial PV / Nordic conditions / bifacial irradiance modeling / performance analysis

1 Introduction

Vertical bifacial PV systems are gaining increasing interest, as their configuration can enable deployment of PV in locations with grid or area limitations [1]. The energy conversion profile of East/West oriented vertical bifacial systems with peaks in the morning and evening will give an improved distribution of PV fed into the grid, and the vertical modules will take up less space and give less shading on the ground compared to South oriented modules with optimal tilt. Additionally, in several countries, for example in the Nordics, the conversion profile of an East/West oriented vertical bifacial system will match better with electricity consumption than South oriented PV [2]. At some locations the annual plane of array insolation of these systems can be higher than optimally tilted monofacial systems, a gain that is found to increase with increasing latitude and albedo [3,4]. The physical structure of vertical PV is suitable for integration in the built environment, for example as railings, walls, or sound barriers. Because vertical bifacial PV systems give less permanent shading on the ground, these types of systems are also suitable in agri-PV [5], i.e., combination of agriculture and PV on the same land area. A drawback with vertical systems is that the installed capacity will be lower per area compared to modules with lower tilt, as longer distances between rows are required to reduce interrow shading losses.

The Norwegian start-up company Over Easy Solar has developed a design for vertical bifacial PV systems employing small modules with the height of one cell mounted in prefabricated rack units. The aim of this design is easier installation on flat roofs. This design is ballast free, giving a light-weight system that enables installation of PV on roofs with weight limitation. The prefabricated units allow for faster installation times. As for vertical bifacial PV in agri-PV, this design is also expected to enable improved combination of PV and green roofs. Despite its smaller size, the Over Easy Solar system is expected to, in most aspects, have similar loss and gain mechanisms as vertical bifacial systems with more regular sized modules.

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Fig. 1. The Over Easy pilot installation at Institute for Energy Technology, Kjeller, Norway.

In planning and financial feasibility analysis of PV systems, as well as for performance analysis of existing systems, accurate methods for simulation of yield are necessary. For systems without measurements of operating conditions, accurate modeling of in plane irradiance is also essential for performance analysis. However, it is uncertain if conventional models used in PV modeling will give accurate results for vertical bifacial PV. For example, the uncertainty in plane of array irradiance modeling with bifacial irradiance models is higher for vertical planes than for optimally tilted planes [6]. In commercial software, the front and rear side irradiance of a bifacial system is typically modeled by different methods. For example, in PVsyst v 7.4, the front side method is a conventional transposition model, while the rear side method is a view factor model, and the modeled plane of array irradiance of the system if the front side is set to East is not the same as if the front side was set to West. In an East/West (E/W) oriented vertical bifacial system the daily insolation will typically be similar on the two sides of the module. Both sides will have direct irradiance half of the day, and only sky diffuse and ground reflected irradiance the other half of the day. For such systems, it should only be important to denote a “front” and “rear” side because of the varying module efficiency on the two sides, not because of different irradiance conditions. Another important aspect for yield simulations is accurately estimating the operating temperature. Module operating temperature models typically utilize empirical coefficients to estimate the heat transfer to the environment. These coefficients depend heavily on system design and are expected to be different for vertical bifacial systems than for conventional freestanding systems.

In addition to the above-mentioned research gaps in the irradiance and temperature models, there can be other loss or gain mechanisms that are prominent in these types of systems compared to more conventional PV system design. Vertical bifacial PV has been previously evaluated in the scientific literature [1,7], but the concept is still new, and more research is needed to document and understand performance and dominant loss mechanisms. More studies in high latitudes, a region where vertical bifacial system installations are supposed to be beneficial, are also needed. Installations with a design similar to the Over Easy Solar system have also been evaluated previously [8], but even less than vertical bifacial systems with regular modules. Consequently, more work is needed on assessing modeling and performance of vertical bifacial PV. Validation, development and standardization of modeling methodology will aid the development of the market for both large scale vertical PV and installations similar to that of Over Easy Solar.

In this work, we assess the use of regular transposition models, as used for monofacial systems, to assess if this approach is good enough to estimate the plane of array irradiance of a vertical bifacial system. Only the irradiance in the planes of the bifacial modules is estimated, irradiance losses such as shading are not taken into account. The irradiance on the “back” side, i.e. the side facing away from the sun, has the same view factor of the ground and the sky as the “front side”. It should therefore be possible to model the ground reflected and sky diffuse irradiance for both sides with the same method, instead of using the more complex methods commonly used in bifacial modeling, e.g. view factor modeling or ray tracing. To evaluate the impact of temperature on the performance of the system, and how it should be included in energy yield modeling, we estimate the heat transfer coefficient used in the PVsyst temperature model, denoted as the U-value, and compare with the standard PVsyst value for free standing system. Moreover, we have analyzed the overall performance and prominent loss mechanisms of three Over Easy Solar pilot installations in Norway.

2 Methodology

The following section describes the Over Easy Solar pilot installations analyzed in this study, and the methodology used in the evaluation of the measured data to assess the use of regular transposition modeling for plane of array irradiance simulations and the performance of the systems.

2.1 Pilot installations and measured data

The Over Easy Solar vertical bifacial PV unit (VPV Unit) consists of a support structure and a specially designed module with the height of one cell, as shown in Figure 1. The aim of this design is to make an easily installed, lightweight (the system is ballast free), vertical bifacial system for flat roofs. This study is based on data from three Over Easy Solar pilot installations in Norway. All the systems are oriented East/West. One pilot is installed at a roof at the Institute for Energy Technology (Fig. 1) and is equipped with sensors measuring both system specific parameters (plane of array irradiance (POA), module

Table 1. Overview of pilot installations.

	Pilot 1	Pilot 2	Pilot 3
Latitude, longitude	60.0, 11.1	59.6, 10.7	69.7, 19.0
Installed capacity [kW]	1.4	2.4	1.4
Module bifaciality	79%	90%	90%
Cell efficiency	20%	22.8%	22.8%
Inverter	Solaredge SE2200, 2.2 kW, power optimizers (P300) per four panels	SMA Sunny tripower, 6 kW (2.4 kW N/S pilot also connected)	SMA Sunny boy 1.5 kW
Time series electrical data	1st July 2022 – 30th May 2023	17th Feb 2022 – 22nd Aug 2023	28th June 2022 – 22nd Aug 2023
Sensors	– East/West POA – Module temperature – GHI – Ambient temperature – Wind speed Length of time series: 1st July 2022 – 31st August 2023	Nearby GHI measurements	Nearby GHI measurements

temperature (modT)) and ambient conditions (global horizontal irradiance (GHI), wind speed and ambient temperature). The POA irradiance is measured in both directions with reference cells installed at the outer rows of the system, i.e. not impacted by the shading within the system. The module temperature is measured with PT elements attached to the glass on both sides of the module. The GHI is measured with a ventilated Kipp & Zonen SMP10-V pyranometer. The rest of the sensors are Meteocontrol sensors. The model of the reference cells is Si-RS485TC. For all three pilots, electrical data is measured at the inverter. The raw data measurements are quality controlled by checking for lacking data and unphysical values. Table 1 presents an overview of the systems. The modules in these installations are early generation Over Easy Solar modules. In newer generation modules the bifaciality is always >90%, the module power is higher, and there are less reflections in the glass.

2.2 Analysis

The analysis takes the following approach: First, conventional POA irradiance modeling (as used for regular monofacial systems) is assessed for modeling the irradiance of vertical bifacial PV. Next, measured module temperature and the performance of the system is analyzed to identify the main factors impacting the performance.

To evaluate POA modeling for vertical bifacial systems, regular transposition modeling is assessed by comparing the simulated results with the measured data from Pilot 1. An albedo of 10% is measured for the roof and used as input to the simulations. The comparison uses data measured July 2022 – August 2023. November – March is removed from the assessment, as in this period snow can either cover the sensor or impact the albedo values, and the very low irradiance values can give increased uncertainties in irradiance measurements. The regular transposition modeling is implemented with pvlib v 0.10.1 [9] to model the irradiance of both sides of the panel. The model is used to estimate the irradiance for the whole day, both when the plane is facing the sun ("front" side), and when it is facing away from the sun ("back" side). First, the measured GHI is decomposed to diffuse horizontal and direct normal irradiance using the erbs [10] and disc [11] models, respectively. Second, the irradiance is transposed to the two planes of the solar modules. Two commonly used sky diffuse models are tested in this transposition process – Haydavies [12] and Perez [13]. The models were chosen after a comparison of all the different sky diffuse models in pvlib, where it was observed that both these models performed well, but in different irradiance conditions. Both models use plane orientation and tilt, diffuse horizontal and direct normal irradiance and solar position as inputs. The Perez model also uses a set of empirical coefficients, in this analysis the 1990 coefficients [13] are used. Based on these inputs, the sky diffuse irradiance and its components (isotropic, circumsolar and horizon) are calculated. The results of the irradiance modeling are evaluated for both cloudy and clear conditions, where clear conditions are defined as timestamps with a clear sky index >0.9. 49% of the datapoints are defined as cloudy conditions, and 51% as clear. The modeling is also evaluated for times when the sensor faces the sun, defined as direct irradiance >0 – "front" side, and when the sensor faces away from the sun – "back" side. The reflection losses in the reference cell are accounted for in the modeling of the irradiance.

Most PV module temperature models use plane of array irradiance (G_{POA}), ambient temperature (T_{a}), wind speed and heat transfer coefficients (U). The heat transfer coefficients are expected to vary with different system designs. In this study, we have estimated the heat transfer coefficients of the PVsyst temperature model (Eq. (1)) based on the measured data at Pilot 1 to estimate the impact of temperature on the performance of this design. The PVsyst model does not account for the effect of wind on heat transfer, but it accounts for absorbed fraction of irradiance (α) and the absorbed energy in the modules converted to electricity, through the module efficiency (η). The result from this assessment is expected to be similar to results for larger sized freestanding vertical systems, but some differences are expected because of the low height and the modules being installed close to the roof.

$$T_m = T_a + \frac{G_{POA} * \alpha(1-\eta)}{U}. \tag{1}$$

In the calculation of the U-value, the combined measured irradiance of both sides is used as G_{POA}. We use the measured module temperature as input, and the approach is consequently not fully compatible with the PVsyst implementation of this model where it is the cell temperature the model estimates. The module temperature is split into morning and afternoon to only use the measurement where the sensor is on the side facing away from the sun. Data from cloudy conditions and irradiance levels lower than 400 $\mathrm{W/m^2}$ is removed from the analysis. α is set to the default value of 0.9, and the efficiency is set to 0.2 for the front side of the module, and 0.16 for the back side of the module. We here use the cell efficiency instead of the module efficiency, as it is a glass/glass module, and we assume that the absorption of energy in the glass is low. This is also no compatible with the PVsyst implementation of the model, where the module efficiency is used. The same is the fact that we use irradiance on both sides. In the PVsyst implementation only front side irradiance is used, as this is a model developed for monofacial modules. In monofacial modules, most of the irradiance on the back side of the modules is expected to be reflected by the backsheet, but a bifacial module will absorb this energy. We therefore choose to include this in the calculation to get a more realistic number on the absorbed energy in the module.

To evaluate the performance of the pilots, we calculate the performance ratio (PR) using the total insolation of the two sides. This is done both with and without considering the bifaciality of the modules. Equation (2) defines $\mathrm{PR}_{\mathrm{tot\ POA}}$ using the insolation of both sides as input, and equation (3) defines the bifacial performance ratio where the bifaciality of the modules also is taken into account, as defined in IEC 61724-1. For Pilot 1 the measured plane of array irradiance is used as input, and for Pilot 2 and 3 the total POA irradiance is modeled based on GHI measurements and estimated albedo. The two different PR values are compared to evaluate the effect of module bifaciality on the performance of the systems. The bifacial PR is further evaluated to identify pronounced system loss mechanisms. This is done by assessing periods of the day and year with low bifacial PR. In this evaluation the effect of interrow shading and angle of incidence of the irradiance is evaluated. Pvlib is used to calculate angle of incidence of the irradiance and the corresponding incidence angle modifier (IAM), as well as the fraction of the module surface shaded because of interrow shading at different time stamps. The reflection losses caused by the angle of incidence (AOI) of the direct irradiance is calculate using the physical IAM model [14] in pvlib. The shaded fraction is modeled with the same method as the bifacial infinite sheds model [15]. The method uses solar position, orientation, tilt and height of the modules, and the distance between the rows as input. To estimate irradiance losses due to high AOI and interrow shading, the direct irradiance component of the modeled POA is multiplied with 1-IAM and the shading factor, respectively. Snow depth is also evaluated as an explanatory factor. Snow depth data is collected from senorge.no.

$$PR_{\mathrm{tot}\ POA} = \frac{\text{Energy output/installed capacity}}{\text{(Front insolation + rear insolation)/1000}} \tag{2}$$

$$\text{Bifacial } PR = \frac{\text{Energy output/installed capacity}}{\text{(Front insolation + module bifaciality} \ast \text{rear insolation)/1000}}. \tag{3}$$

3 Results

3.1 Irradiance modeling

Figure 2 shows the modeled monthly POA insolation of an East/West (E/W) vertical bifacial system compared to the insolation of a South-oriented, optimal tilted monofacial system at the location of Pilot 1, before system irradiance losses are taken into account. One year of measured GHI data is used as input. The irradiance is modeled with regular transposition models as implemented in pvlib, illustrating the expected differences. The figure shows total insolation, sky diffuse insolation, and ground reflected insolation modeled with an albedo of 0.1 and 0.4. We observe from the figure that for several months of the year, the E/W insolation is highest, and both the sky diffuse and ground reflected irradiance is contributing to this. Annually, the modeled E/W vertical bifacial POA insolation is 4% higher than the monofacial South-oriented optimal tilt POA. The contributions of ground reflected irradiance are increasing with increasing albedo. It is generally known that reflected irradiance is important for vertical and bifacial systems and that this is something that should be considered accurately in irradiance modeling, but the large share of sky diffuse irradiance suggests that it is essential that also this factor is modeled correctly.

Figure 3 shows the difference between the total modeled and measured irradiance at Pilot 1, using two different models for sky diffuse irradiance in the modeling. The results are shown for cloudy, clear and all conditions, and for “back” and “front” side irradiance as well as for the total irradiance. The modeled irradiance is underestimated for ratios above 1 and overestimated for ratios below 1. Figure 4 shows the modeled results compared to measured value for all the datapoints in the analyzed period, divided similarly as for Figure 3. The uncertainty in the POA

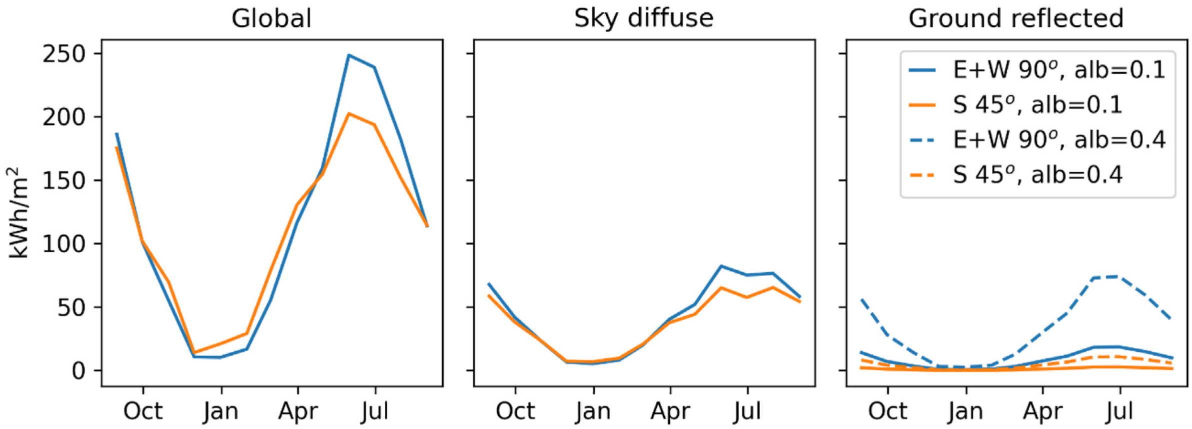

Fig. 2. Global, sky diffuse and ground reflected monthly insolation, before system irradiance losses are taken into account, modeled with regular transposition modeling using one year (Sept. 2022 – Sept. 2023) of the GHI data from Pilot 1 and an albedo (alb) of 0.1 and 0.4.

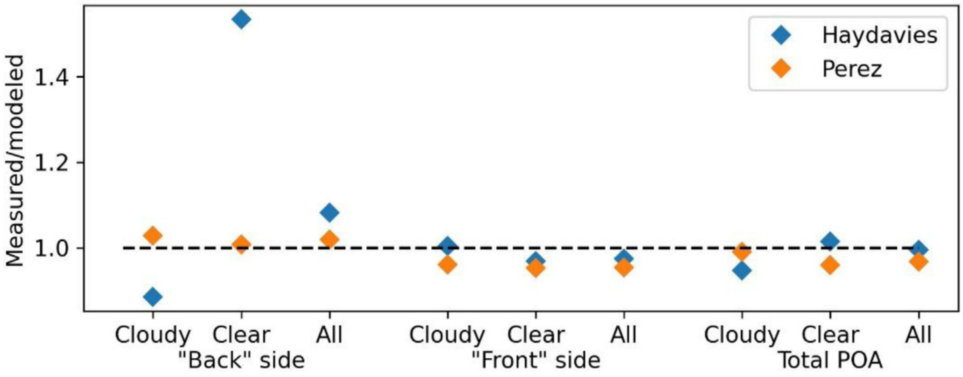

Fig. 3. The ratio between the aggregated measured and modeled irradiance in the analysis period using both the Haydavies and Perez sky diffuse model. The results are shown for cloudy and clear conditions, and for when the sensor is facing away from the sun ("back") and when the sensor is facing the sun ("front").

modeling is not only related to the transposition modeling, but also of the modeling step where GHI is decomposed to DHI and DNI. The uncertainty could have been reduced by using measured values of DHI and DNI.

When the sensor is facing away from the sun ("back" side), the measured irradiance only consists of sky diffuse and ground reflected irradiance. In these periods using the Perez model gives overall best results, while the Haydavies model overestimates at cloudy conditions and underestimates at clear conditions. In the scatterplot in Figure 4, we observe that it is mostly around 50–150 W/m the Haydavies model overestimates the irradiance at cloudy conditions, and that it is at higher irradiance we underestimate when using the Perez model. At clear conditions, the Haydavies model underestimates at all values, but the Perez model only underestimates at higher values. This difference between the two models is also shown in Figure 5, showing the modeled sky diffuse isotropic irradiance with the two models for two almost clear and two cloudy days. For the two first clear days, the Haydavis model predicts lower sky diffuse irradiance than the Perez model, and for the two last cloudy days higher than the Perez model.

When the sensor is facing the sun ("front" side), the sensor is additionally measuring direct and circumsolar irradiance, where circumsolar irradiance is estimated with the sky diffuse irradiance models. We observe fewer clear trends on the deviation in the scatterplot in Figure 4 on the front side compared to the back side. This can be explained by the fact that front side irradiance is dominated by direct irradiance, and that the uncertainty in the modeling of this effect is less impacted by the irradiance conditions than the diffuse irradiance. In Figure 3, we observe that when using the Perez sky diffuse model, the irradiance is overestimated for both cloudy and clear conditions, and the Haydavies model yields better results. However, Figure 5 shows that the Perez model also predicts lower circumsolar irradiance than the Haydavies model. The reason why the Perez model still overestimates the irradiance is because of the contribution of horizon brightening/darkening (also shown in Fig. 5) that also is part of this model. Horizon brightening increase the modelled irradiance on both the "front" and the "back" side, but because the total underestimation of the circumsolar irradiance is smaller than the underestimation of the sky diffuse irradiance, this is more visible on the front side. This shows that the choice

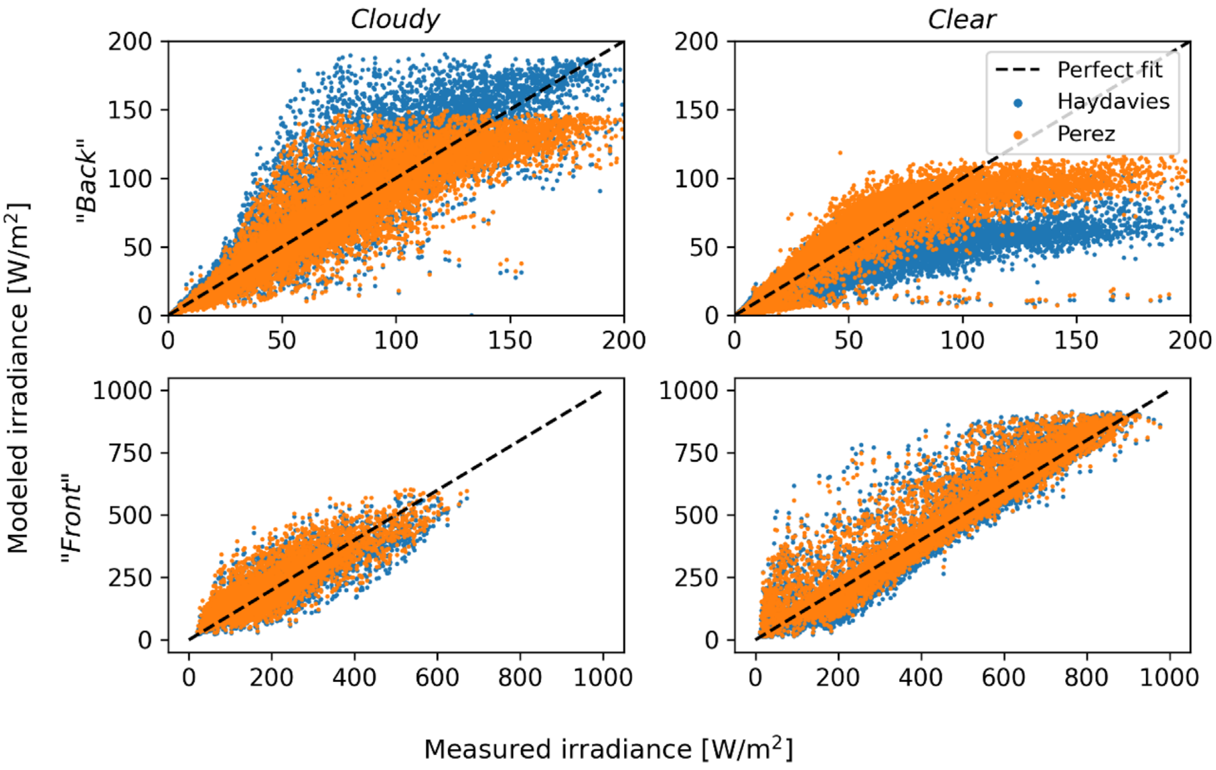

Fig. 4. Measured versus modeled irradiance for all datapoint in the analysis period using both the Haydavies and Perez sky diffuse model. The results are shown for cloudy and clear conditions, and for when the sensor is facing away from the sun ("back") and when the sensor is facing the sun ("front").

of the diffuse irradiance model can have an impact on the modeled POA irradiance, and that the best fitting model can vary with different irradiance conditions (clear/cloudy weather). In total, the modeled vertical POA irradiance for this location is overestimated 0.4% when using the Haydavies model, and 3.4% when using the Perez model. The high accuracy of the results using regular transposition modeling indicate that e.g. computational demanding ray tracing models commonly used for back side irradiance may not be necessary for modeling the global irradiance in a vertical plane. It may, however, be more complicated to model the effective irradiance within the system, where the row in front blocks parts of the direct irradiance as well as the view to the ground and the sky, and the system itself shades the ground.

3.2 Temperature analysis

Figure 6 shows the U-values estimated from the measured data compared to the default value of 29 $\mathrm{W/m^2K}$ suggested in PVsyst v 7.4 for free standing systems. The median calculated U-value is 55 $\mathrm{W/m^2K}$, much higher than the standard U-value used in PVsyst. This indicates that the heat exchange with the surrounding air is more efficient than for regular free-standing systems. Carr et al. [16] observe similar levels of heat exchange (U-value of 56 $\mathrm{W/m^2K}$) for vertical systems with normal sized modules. These high values can be explained by both the vertical design, but it can also be related to the type of modules. In a vertical design, the air can easily move on both sides, enabling good ventilation, and both sides of the modules face the sky. Vertical modules are also expected to be more impacted by wind. For the data analyzed in this work, the measured wind speeds on the roof close to the system are low, typically less than 2 m/s. At these wind speeds we did not find any correlations between measured wind speed and calculated U-values. In both the system in this work and in the work by Carr et al., the modules are bifacial glass-glass modules. It could be expected that these modules have different physical properties with respect to heating and cooling than monofacial modules with polymer backsheet that has been used in most previous studies where U-values are estimated. For the data studied in this work, the high heat exchange can additionally be related to the shape of the module. It has been observed that it can be some temperature variation within the module, and that it typically is coldest closes to the edge [17]. In a small module, large parts of the module are close to the edge region.

The lower temperatures of the system will impact the performance positively through lower thermal losses in the modules. However, if the roof itself is heating up in the sun, the close mount to the roof can impact negatively due to increasing ambient temperatures. It has been shown that U-values estimated from data can vary between different sites with identical modules and same type of mounting [18], and the U-value should be estimated for more Over Easy Solar installations to get a robust value to use in yield simulations.

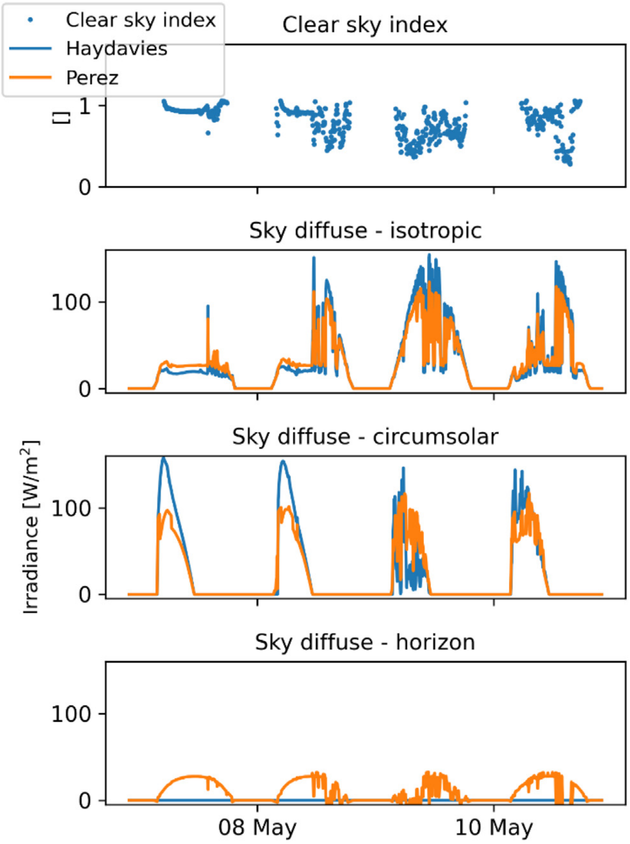

Fig. 5. Clear sky index and modeled components of the sky diffuse irradiance using the Haydavies and the Perez model.

When modeling module temperatures, a *U*-value of $50\,\mathrm{W/m^2K}$ fits well for most of the data, but slightly underestimates at higher temperatures. A *U*-value of $45\,\mathrm{W/m^2K}$ yields a good fit for most temperatures, shown in Figure 6. With a *U*-value of $29\,\mathrm{W/m^2K}$, the module temperature is overestimated by 5–10 . As the operating temperature directly affects the module efficiency, this will impact the energy yield. Assuming a thermal coefficient of $-0.38\%/°\mathrm{C}$, the temperature overestimation done in PVsyst would give 1.9–3.8% too high temperature losses in a yield calculation.

3.3 Performance analysis

As described in Section 2.2, the PR values for Pilots 2 and 3 are calculated with modeled irradiance. There are consequently uncertainties in this reference value, as there are uncertainties in the albedo input. Additionally, we see from Section 3.1 that in the comparison with measured POA irradiance values at Pilot 1, we overestimate the irradiance, which would give an underestimation of the performance. Consequently, we have uncertainties in the absolute PR values, but we still think we can learn something about the loss mechanisms in the systems from the trends in the PR.

Figure 7 shows the PR calcuated with the irradiance of both sides ($\mathrm{PR}_{\mathrm{tot\ POA}}$) and the bifacial PR, as well as monthly energy yield and insolation for the three pilot installations. From the difference between the two calculated PR values, we observe that module bifaciality impacts the performance in periods with high irradiance, especially for Pilot 1 where the bifaciality is only 79%. We observe a clear seasonal development of the performance, with lower PR values in the winter months. From the bifacial PR values with high time resolution shown in Figure 8 for one cloudy and one clear day, we observe that on the clear day the bifacial PR is gradually increasing in the morning, decreasing in the afternoon, and we have a dip in the middle of the day. These trends are not observed to the same degree for the cloudy day. The increase and decrease in the bifacial PR for the clear day corresponds to the interrow shading factor and the angle of incidence of the direct irradiance of the module plane that faces the sun ("front" side), also shown in Figure 8. It seems reasonable that interrow shading and high AOI of direct irradiance resulting in reflection is the cause for these losses, as we expect that both these factors will have highest impact on clear days. Figure 9 shows the monthly insolation losses caused by interrow shading and reflections caused by high AOI of the direct irradiance relative to the total plane of array insolation. We observe that the relative losses are highest in the winter months, and consequently contributing to the lower PR values in this period.

There are also other explanatory factors for the low PR values calculated in the winter months for all pilots. In the winter months, all PV systems in Norway experience losses because of the general low irradiance, also documented in Figure 7, where both the module and inverter efficiency are lower than at more optimal irradiance conditions [19]. Pilot 3, which is situated above the polar circle, has close to zero irradiance in the months December-February. The low solar elevation during this season also gives increased losses due to shading from objects around the system. There are, however, also losses caused by snow, but the snow loss trends differ compared to tilted systems. For the Over Easy Solar pilots, only thick snow layers submerging the system leads to losses. Figure 10 shows the snow depth for the analyzed period for the three locations, and the distribution of daily snow depth (for days with snow depth >0) in the period 2012–2023. Both for the analyzed period and historically, Pilot 3 is the only location where the snow depth is large enough to submerge the system for longer periods. In this regard it is also important to notice that the snow depths on roofs typically are lower than on the ground, because of higher wind erosion or heat leakage from the building [20]. Thin snow layers will, on the other hand, only increase the albedo and the irradiance of the system. The importance of this effect will depend on the irradiance levels in the periods with snow cover. From Figure 10 we see that the locations of Pilot 1 and 2 in the analyzed period have snow cover in the period December to March. For the year 1st of July 2022 – 30th of June 2023, the insolation in this period is 13% of the annual insolation for Pilot 2 and 16% for Pilot 1. Pilot 3 has snow

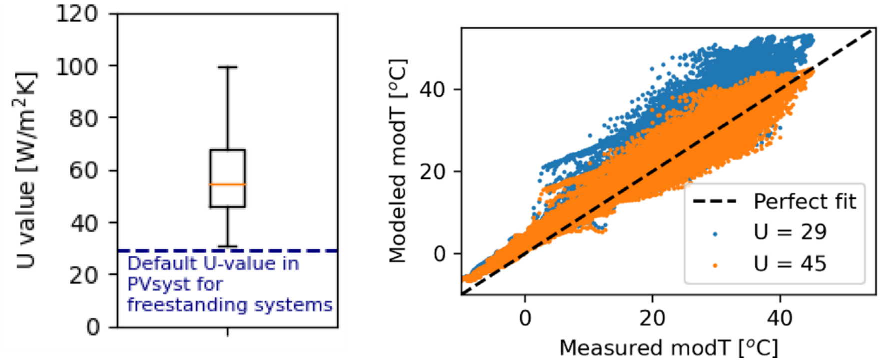

Fig. 6. Left: U-values estimated from the measured data compared to the default value in PVsyst. Right: measured versus modeled module temperature (modT) using both a U-value of 29 W/m^{2}K and a U-value of 45 W/m^{2}K in the modeling.

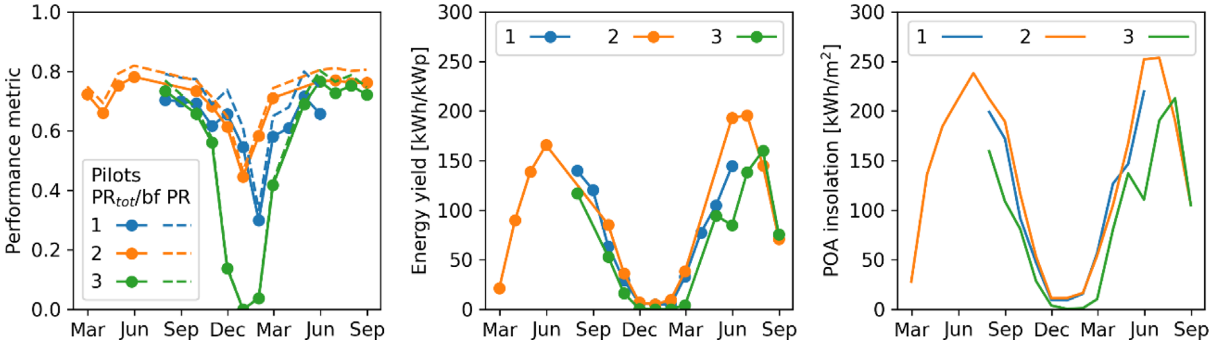

Fig. 7. Monthly $PR_{tot\ POA}$ and bifacial (bf) PR (left), corresponding energy yield (center) and POA insolation (right) for the three pilot systems, months with lacking data excluded.

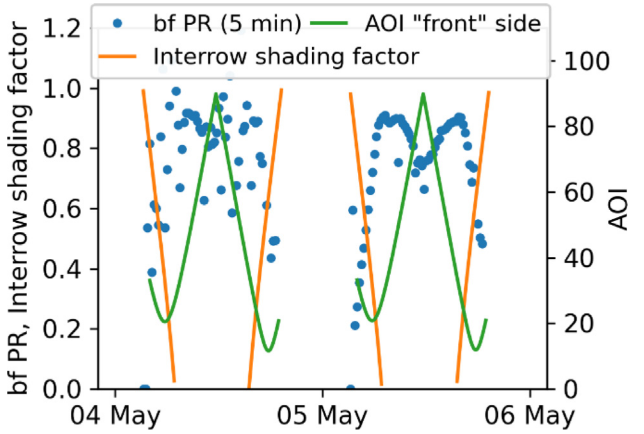

Fig. 8. 15-minute bifacial PR values for Pilot 2 for one cloudy and one clear day plotted with the interrow shading factor and the AOI of the direct irradiance of the module plane facing the sun (“front” side).

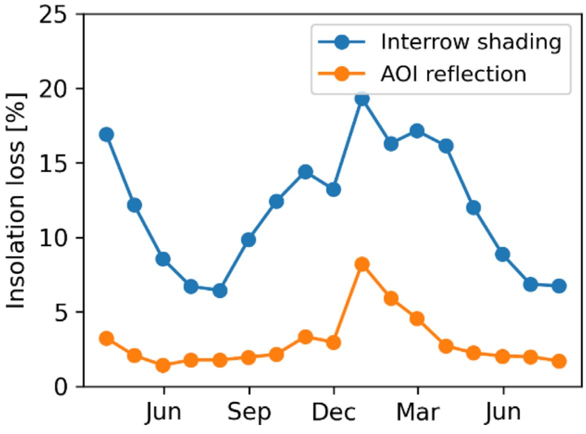

Fig. 9. Monthly insolation losses caused by interrow shading and reflections at high AOI.

cover also in April, and the insolation in the period with snow cover is 25% of the annual insolation. This is consequently not a gain mechanism we will expect every year, but if the snow lasts until late March/April when there is increasing irradiance the gain can be significant. The Over Easy Solar system is consequently expected to be less negatively impacted by snow than tilted systems, but more than a vertical system with larger modules that requires more snow to be submerged.

The aim of this performance analysis is to identify loss mechanisms that are typical for the Over Easy Solar configuration. Some of the losses impacting the performance are, however, related to the fact that these are pilot systems, i.e. small systems with 1st generation modules, and downtime periods. Because the systems are small, the

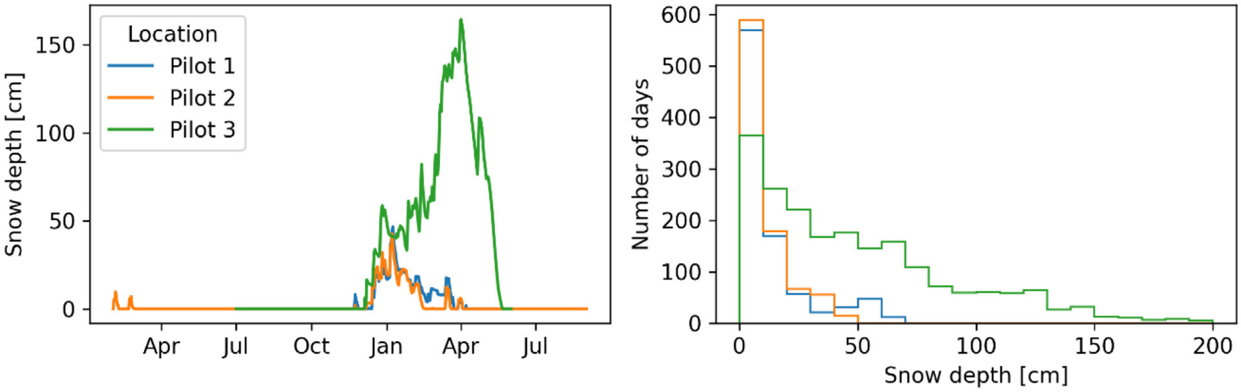

Fig. 10. Snow depth on the ground on the location of the pilot systems in the analyzed period (left) and histogram of number of days (with snow depth >0) for different snow depths in the period 2012–2023 (right).

inverter sizing is not optimal. This is especially true for Pilot 1 where both the optimizers and the inverters are over dimensioned. The 1st generation modules of the studied pilots have lower bifaciality and higher reflection losses than newer generations.

Overall, we find that the module bifaciality, interrow shading, and high angles of incidence in the middle of the day, are giving increased losses for the Over Easy Solar configuration in E/W orientation. But we also expect less snow and thermal losses, and also the high annual insolation for vertical bifacial E/W systems are expected to contribute positively to the total output. In Norway, the Over Easy Solar installations are found to have 28–51% higher specific yields than the conventional systems with PV modules on flat roofs installed with E/W orientation and 10° tilt [21]. We expect the results of this study to also be valid for E/W vertical bifacial system with more regular sized modules. The results on POA irradiance modeling, and losses because of module bifaciality, interrow shading and high angle of incidence in the middle of the day should be directly applicable. The variation in the physical structure means that we would expect other temperature coefficients and less risk of submerging in snow for regular sized modules. However, snow can be a challenge for vertical systems with regular modules close to the ground, and in locations with snow accumulation around the modules because of snow drift.

4 Conclusion and further work

In this study we assess the use of regular transposition modeling for plane of array irradiance modeling for vertical bifacial PV, and we evaluate the performance of Over Easy Solar pilot installations in Norway to identify prominent loss mechanisms. With regular transposition modeling plane of array irradiance is overestimated by less than 1%. However, accurate albedo input and choice of sky diffuse model impact the accuracy of the modeling. Using measured DNI and DHI data could have increased the accuracy in the modeling further. For the studied location, the sky diffuse irradiance model that gives best results is impacted by the irradiance conditions, i.e. the clear sky index. It can, however, be more complicated to model the effective irradiance within the system, where the row in front blocks the view to the ground and the system itself shades the ground.

We find that the expected insolation of E/W vertical bifacial systems in Norway is higher than for optimal tilt most months of the year (4% higher annual insolation for the modeled case), and that this is increasing with increasing albedo, suggesting that snow can have a positive impact. We also report that the Over Easy Solar configuration shows good heat transfer capabilities, exemplified through the median computed heat loss coefficient of 55 $\mathrm{W/m^2K}$, indicating low thermal losses in the PV modules for this system. On the other side, we show that E/W vertical bifacial systems can have significant losses due to module bifaciality, interrow shading, and reflections caused by high angle of incidence of the direct solar irradiance in the middle of the day. The magnitude of these losses will however vary with operating conditions (weather and latitude) and module technology. For the Over Easy Solar configuration with modules with low height, there is also a risk for snow submerging for thick snow layers.

Further planned work is to develop and validate simulations taking irradiance losses and other identified system losses into account and suggest an enhanced procedure for modeling of vertical bifacial PV systems. With the validated modeling approach, we will simulate the potential of vertical bifacial at different latitudes and weather conditions, and with different albedos and orientation.

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Conflicts of interest

The authors have nothing to disclose.

Data availability

The data associated with this article is not publicly available.

Author contribution statement

Mari B. Øgaard performed most parts of the data analysis and wrote the paper. Vilde S. Nysted performed the analysis on temperature and contributed to the writing process. Sigrid Rønneberg, Gaute Otnes, Sean Erik Foss, Trygve Mongstad and Heine N. Riise participated in planning of the work, discussion of the results and gave feedback in the writing process.

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