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# PRACTICAL COMPARISON BETWEEN VIEW FACTOR METHOD AND RAY-TRACING METHOD FOR BIFACIAL PV SYSTEM YIELD PREDICTION

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ABSTRACT: View-factor and ray-tracing are the most commonly used methods to estimate the irradiance incident on the rear side of modules in bifacial PV systems. The view-factor method is used in well-known commercial software, such as PVsyst and SAM. On the other hand, the ray-tracing method is not commercialized yet and is rather complicated and time consuming to use. However, it is more accurate and suitable for complicated geometries. Despite the mentioned advantages and disadvantages in both models, a practical comparison of bifacial PV yield predictions using both methods on a system level is not available in the literature to the best knowledge of the authors. This paper determines the accuracy of the view factor method with respect to ray-tracing. The rear-side irradiance is significantly lower in view factor method and mean bias error (MBE) is up to 19.7 % lower than in ray-tracing method.
Keywords: Bifacial, Modelling, PVsyst, Ray tracing, System Performance

## 1 INTRODUCTION

As PV industry is now moving their main manufactural stream to mono-based PERC, its market share in industry has already reached more than 40% in 2018 and is expected to dominate the market before 2026. International technology roadmap for photovoltaic (ITRPV) roadmap also forecasts that bifacial modules would dominate the worldwide PV market in 2029 with a share of 60% [1].

Besides, the production line of the mono-based PERC module does not need a big effort to move to bifacial technology. Hence, there are already efforts on bifacial system performance modeling. Bifacial PV modules can use the solar irradiance from both the front and the rear side. The system performance of bifacial PV technology, however, depends not only on the PV module properties but also on its geographical design that strongly influences the irradiance received on the rear side of the modules. Accordingly bifacial PV system performance tools are considered rather important to predict energy yields, and several tools already exist in the market. Nevertheless, as bifacial PV power plants just started to be built at a large scale, the comparison of different tools and their validation are still not comprehensively performed or commonly published.

## 2 INTRODUCTION OF MODELS AND TOOLS

The modelling of bifacial yield requires an accurate estimation for the rear side irradiance of the modules. Two main approaches exist to achieve this estimation: the "view-factor" method and the "ray-tracing" method.

The view factor method is known as a method easy to implement but more suitable for small system sizes or rather for single modules. Several commercial PV performance tools, such as PVsyst [2], SAM [3] or ISC Konstanz tool [4] apply the view factor model and are already often used in the market.

On the other hand, the ray-tracing model enables the complex simulation of large scale system even considering the influence from mounting structures. This method, however, requires large amounts of computing time. Ray-tracing approaching tools are not yet commonly used in the market but research institutes, such as NREL [5], EDF R&D [6] or Fraunhofer ISE [7], are applying this method.

The ray-tracing method is already examined and showed annual error ranges of DC power less than 6.8% on a small scale bifacial PV system [8], however validation of commercial tools with bifacial PV systems is not yet published to the author's acknowledge.

This paper investigates two main models for bifacial PV system performance prediction, view factor- and ray-tracing model and compares both models with monitoring data.

### 2.1 View factor method and PVsyst

The view factor method is based on the ground-reflected irradiance using a configuration factor called the view factor. View factor($F_{i\to j}$) is the fraction of radiation which is leaving from Ai and reaching to Aj. This concept is conceived from the heat transfer theory.

$$F_{i\to j} = \frac{1}{A_i}\int_{A_i}\int_{A_j}\frac{cos\theta_i cos\theta_j}{\pi r^2}dA_i dA_j \quad (1)$$

The view factor is divided with ground surface into shadow as well as non-shadow areas to calculate the irradiance radiating from ground to module surface. The irradiance reflected from the ground is strongly influenced by the ground albedo $\alpha$.

$$I_{refl,r} = \alpha GHIF_{A_{nsh}\to A_M} + \alpha DHIF_{A_{sh}\to A_M} \quad (2)$$

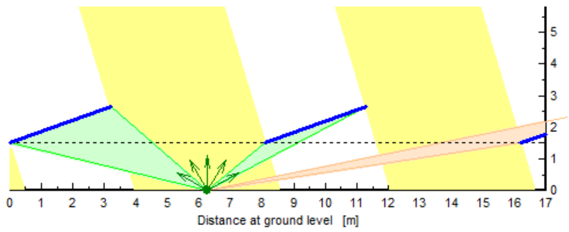

Figure 1 Illustration of view factor to show how the rear-side irradiance is evaluated (limit angle=13.3).

The commercial PV performance tool PVsyst applies this model for their irradiance modeling approach on front and rear side of modules. This tool was initially developed at the University of Geneva in 1992 and applied bifacial PV technology since 2017.

In this program, the irradiance at rear side is calculated for five points on the rear side and averaged over them.

The sky diffuse contribution on the rear side is calculated in 2-dimensions by an integral over the part of the sky that is visible from the rear side of the modules. The integration considers the angle of incidence and the IAM losses (see Figure 1). Besides, the light re-emitted of the ground has an isotropic distribution.

2.2 Ray-tracing method and Fraunhofer ISE's tool

The ray-tracing model is easy to define the complex configuration design, while the calculation consumes big amounts of computer time. Nevertheless, this method may solve a number of problems simultaneously: the calculation of rear side irradiance including its inhomogeneity that is influenced by the mounting structure. Complex geometries, topology, edge effects, or mutual shading effects can also be easily taken into account.

The approach of Fraunhofer ISE is based on *Radiance*, a powerful lighting simulation program based on backward ray tracing calculation. One of the Radiance tools named *Gendaylit* [9] creates a complete sky radiance distribution using the Perez model for any pair of global and diffuse irradiance. The defined model, including geometry and surface and ground materials, may be rendered as an image, and numerical values of irradiance may be calculated for arbitrary positions. "Irradiance measurements" in Radiance are performed as "seen" by virtual sensors on front and back side of defined PV cells.

The whole bifacial modelling process from optical (Radiance) is controlled by a Python tool package.

## 3 BIFACIAL PV SYSTEMS

The performance of the models along with the real bifacial installations in outdoor operation is an important factor in order to cross check the two different models with its validations. First results of validations were already presented in [6], [7] and [8]. Two more validation cases are considered in this study in order to cover more types of configuration, such as array size, tilt angle and albedo, in different climate, one in Germany and the other in South Korea.

3.1. System 1 – Single string PV system

System 1 represents a single string consisting of 8 bifacial modules on a roof at Korea Polytechnic University, Siheung-city in South Korea. 8 modules with 82% of bifacility are mounted on a test rack with unobstructed rear surface with 37° of tilt angle. The system orientation is 217° (south-west direction) and height from the surface is 1.5 m. The front irradiance, rear irradiance and module temperature are monitored with Si-reference sensor. The string can be seen in Figure 2. Underneath the modules, the white sheet covers the ground in order to increase the ground albedo. Albedo value of white sheet is set as 55% and is derived from 2 weeks of measurement. The white sheet is formed with 5m of depth, 10m of length and approximately 50 cm ahead the module front edge

Monitoring period on this system is partly limited within the monitoring year 2017. The available monitoring data used for the analysis are listed below.

- Irradiance front: 01.July – 31.Dec
- Irradiance rear: 09.Jan – 08.Mar & 19.Oct – 26.Oct

Figure 2: (System 1) Single string with 8 bifacial modules on the roof of Korea Polytechnic University

3.2. System 2 – 194.4 kWp fixed-system

System 2 is 194.4 kWp size of PV power plant with bifacial PV modules located in Heggelbach, Germany. This system is an agrophotovoltaics (APV) pilot plant by Fraunhofer ISE.

The modules are 60-cells bifacial modules with 60% of bifaciality and they are installed with 234° (S: 180°, N: 0°) of azimuth angle and 20° of tilt angle. The whole system is installed 6.58 m over ground and the pitch distance is 8.1 m. This large height and pitch distance is designed due to tis APV purpose and assume the ground with crops have annually average ground albedo as 20%.

The system is monitored with Si-reference sensor on the front and the rear side and thermal sensors on the back of the modules. System 2 can be seen in Figure 3.

Figure 3: (System 2) 194.4 kWp APV system in Heggelbach, Germany.

| | System 1 | System 2 |
|---|---|---|
| Module type | 60 cells n-type | 60 cells n-type |
| System peak power | 2.28 $kW_p$ | 194.4 $kW_p$ |
| Tilt angle | 37° | 20° |
| ground cover ratio (GCR) | - | 40% |
| Ground albedo (%) | 55% measured | 20% estimated |
| Location/Climate | South Korea/ temperate climate with four distinct seasons | Germany/ moderately continental |

Table 1: Geometrical configuration of system 1 and system 2.

## 4 TECHNICAL SETUP FOR COMPARISON

Korea Polytechnic University and Fraunhofer ISE have modelled and simulated both systems with PVsyst and Fraunhofer ISE's inhouse tool respectively. As two models are adopted in two different tools, there are some technical issues that should be answered. This chapter describes such issues and discussions in order to compare both models in identical conditions.

4.1. Technical difference between models

Fraunhofer ISE's tool can use arbitrary input time intervals, while hourly data is the minimal time interval in

PVsyst. Therefore, input weather data is aggregated into hourly data for PVsyst operation. Table 2 describes the different input data used in each tool.

| | | |
|---|---|---|
| Weather data | PVsyst | Hourly aggregated values from 5min measurement data |
| | ISE tool | 5 min measurement data |
| Mounting structure | PVsyst | No Mounting structure |
| | ISE tool | 3D geometry |

Table 2: Dissimilar input parameters used in both tools

The following bullet points list are the input parameters, identically applied in both tools

- Geometrical configuration of the system installation
- Ground albedo

In PVsyst, the system design is often recommended internally and therefore, sometimes the simulation can be denied to perform if the system design is not a commercialized standard design, such as a ground-mounting or a roof-top design. Beside, this recommendation is on the basis of the optimal module azimuth angle (south-facing in north hemisphere) to maximize its yield. This method is often not able to perform the specialized PV system.

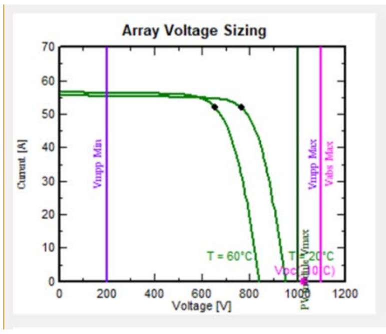


Figure 4: Inverter sizing in PVsyst for System 2 which is denied in simulation. The maximum array voltage ($V_{max,array}$) is 1000V and this value is beyond maximum voltage (Vmax) of PV modules in array.

As already mentioned in chapter 3, the System 2 is designed for the purpose of APV and therefore this system design was denied to be modelled in PVsyst as shown in Figure 4. This is due to the mismatch in maximum array voltage ($V_{max,array}$) between the data from datasheet and the calculated value. Hence, in order to run the simulation in PVsyst, 1000V of $V_{max,array}$ is essentially set to 1100V.

### 4.2. Data filtering

System 1 and 2 are operating over several months and the measurement data was recorded with 5 minute time intervals.

For the input of modelling, weather files were constructed from irradiance and temperature measurements on site. Global Horizontal Irradiance (GHI) was measured using CMP10 pyranometers, Diffuse Horizontal (DHI) using a SPN1 pyranometer. Data from the pyranometers were filtered according to the following rules:

- GHI and DHI values below 0 W/m² were removed
- If DHI > GHI, DHI is set to GHI value
- GHI and DHI are set to zero for sun height < 0°

In order to compare two modelling result in different form of time intervals, one from PVsyst and the other from Fraunhofer ISE's tool, some conditions are set:

- All data is aggregated into hourly average value and compared with as well aggregated measurement data.

Finally, in order to remove the effects of snow, and environment shading that are not considered in the simulation, the points for which difference between measured and simulated is greater than 50% have not been considered, assuming that such difference are due to external condition, not to the modelling. The same is true for time steps that show higher rear-side measurements than simulated front-side irradiance.

## 5 COMPARISON MTEHOT AND RESULT

### 5.1. Comparison method

The Root Mean Squared Error (RMSE) is a measure of accuracy and is proportional to the size of the squared error. Thus larger errors have a disproportionately large effect. It can be expressed in the unit of the data or in percentage. It is calculated with the following formulas:

$$RMSE_{absolute} = \sqrt{\frac{\sum_{i=1}^{N}(sim_i - meas_i)^2}{N}} \qquad (3)$$

$$\mathrm{RMSE}_{relative} = \frac{RMSE_{absolute}}{mean(meas)} \qquad (4)$$

The Mean Bias Error (MBE) is also a measure of accuracy. It gives the average error between the simulation and the true value. It can be expressed in the unit of the data or in percentage. It is calculated with the following formulas:

$$MBE_{absolute} = \frac{\sum_{i=1}^{N}(sim_i - meas_i)}{N} \qquad (5)$$

$$MBE_{relative} = \frac{MBE_{absolute}}{mean(meas)} \qquad (6)$$

The indicator more relevant to the market is the Mean Bias Error (MBE), as it represents the amount of energy under or over-predicted by the model. As discussed, the mentioned systems in section 2 are analyzed with above error indicators and the results are discussed in the next sections.

### 5.2. Comparison result

Irradiances on both sides, front and rear side are measured in both systems with 5 mins time intervals. The irradiance simulation results are showing the same tendency in both systems. The overall deviation range of front-side irradiance is between 6.5% and 11.1% for RMSE which are higher than the expected range [6] due to the spectral mismatch from Si-reference sensor (Figure 5). Besides, the higher deviation of front irradiance at system 1 requires the albedo measurement over the year to obtain the precise albedo value.

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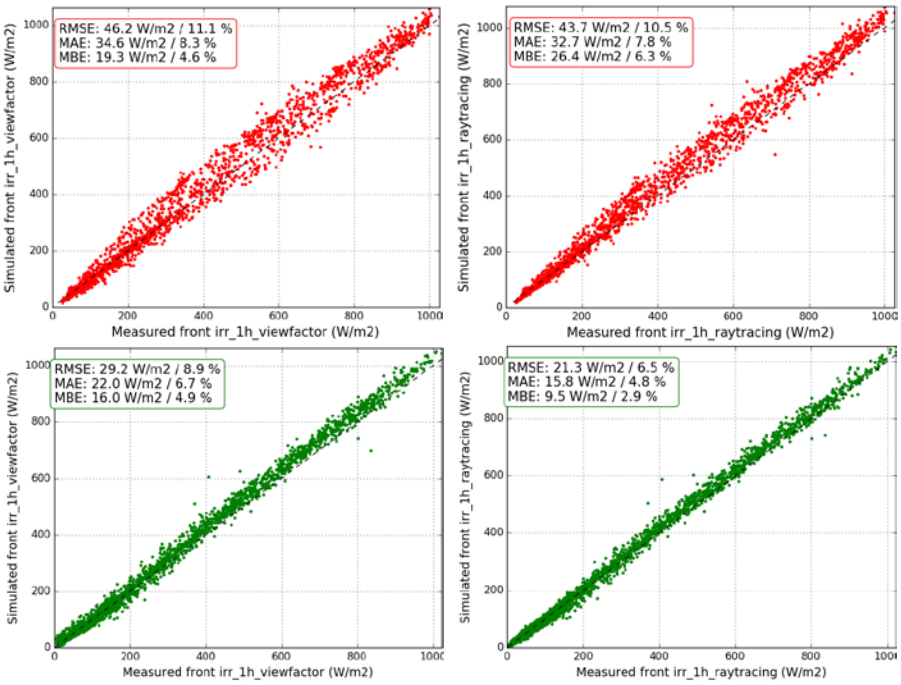


Figure 5 Deviations of front-side irradiance on System1 (top) and System2 (bottom). The view factor model (left) shows a MBE of 11.1% and 4.9% and the ray-tracing models (right) a MBE of 10.5% and 2.9% .

The rear-side irradiance derived from PVsyst is mostly lower than the one from Fraunhofer ISE tool. This can be observed as a time serial plot in Figure 6 for two days in winter and two days in summer. The difference on rear-side irradiance comparing to the measurement data is more obviously shown in Figure 7. The MBE values from the view factor method are -21.5% and -23.2% for system1 and system2 respectively, while the ray-tracing method shows a MBE of -3.9% for system 1 and -3.5% for system 2.

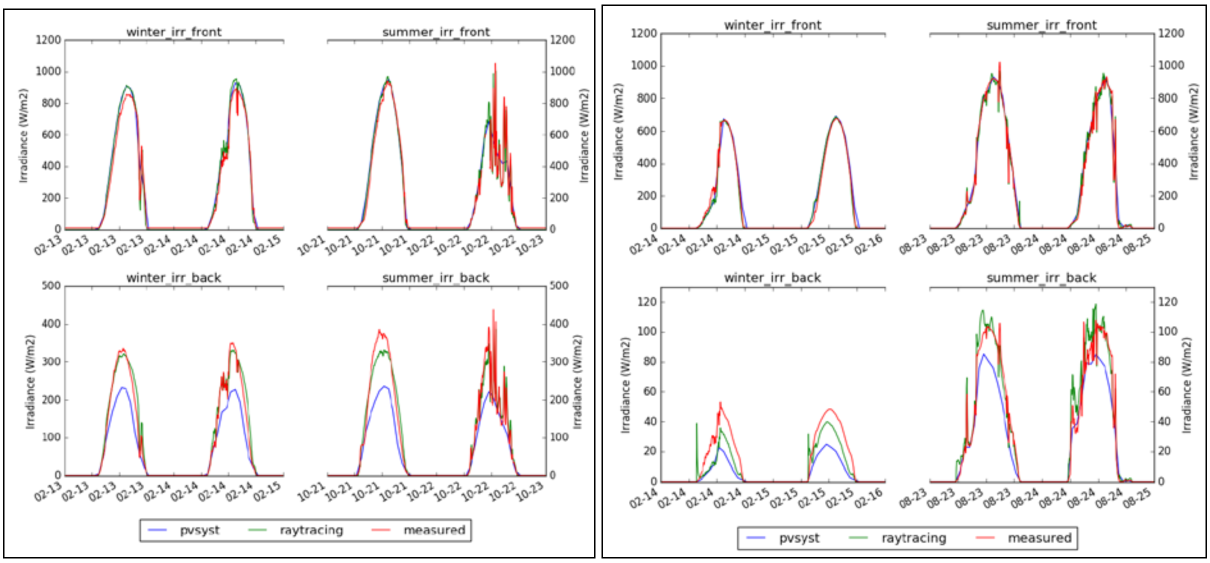


Figure 6: Irradiance comparison of two models using System 1 (left) and System 2(right). Two days of winter (February) and two days of Autumn (October for System 1) / summer (August for System 1) are chosen.

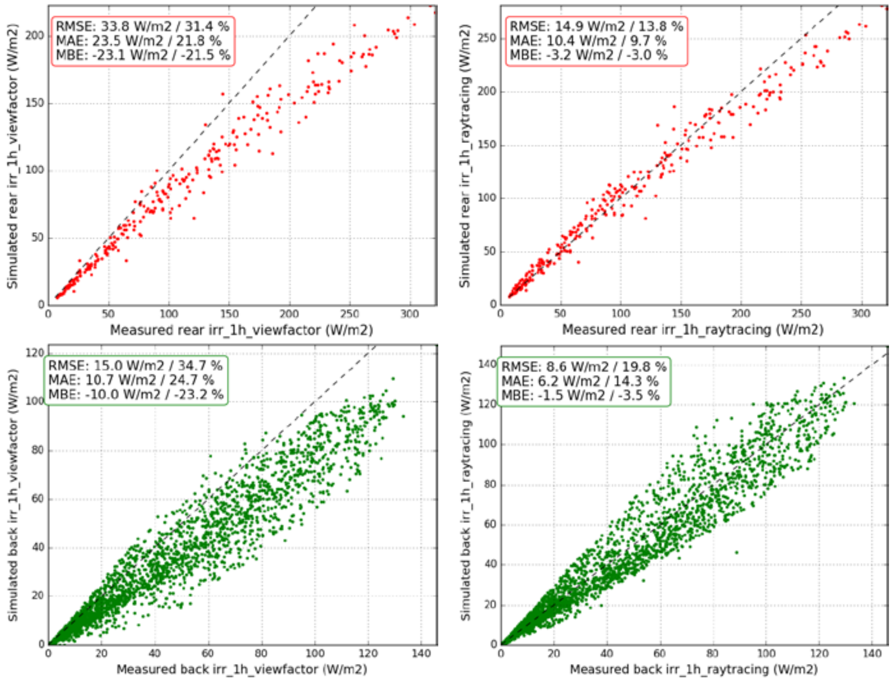


Figure 7 Deviations of rear-side irradiance on System1 (top) and System2 (bottom). The view factor model (left) shows a MBE of -11.8% and -23.2% and the ray-tracing models (right) a MBE of 19.6% and -3.5% .

### 5.3. Summary

The performance of the models is summarized in Table 3. The deviation of the front-side irradiance is between 4.6% and 11.1% for view factor result and between 2.9% and 10.5% for ray-tracing method. The deviation of rear-side irradiances is significantly different. The RMSE of the rear-side irradiance is between 31.4% and 34.7% for view factor result and between 13.8% and 19.8% for Fraunhofer ISE's tool. The MBE of the rear-side irradiance is between -23.2 and -21.5% for PVsyst result and between -3.5% and -3.9% for Fraunhofer ISE's tool.

System 1 that consists of one single string shows generally high deviation in both tools. This is firstly because the 55% of albedo value is derived from the short term of measurement data and secondly albedo deviations from the possible spectral mismatch or from the different climate are not considered. Hence, the comparison can be improved by applying full albedo measurement data.

| | | **Syst 1** RMSE/MBE (%) | **Syst 2** RMSE/MBE (%) |
|---|---|---|---|
| **Irrad Front** | PVsyst | 11.1 / 4.6 | 8.9 / 4.9 |
| | ISE tool | 10.5 / 6.3 | 6.5 / 2.9 |
| **Irrad Rear** | PVsyst | 31.4 / -21.5 | 34.7 / -23.2 |
| | ISE tool | 13.8 / -3.9 | 19.8 / -3.5 |

Table 3: Summary of the performance of the two tools PVsyst (applies view factor model) and Fraunhofer ISE's tool (ISE tool, applies ray-tracing model). Errors are given with regard to the measurement values.

## CONCLUSION

Accurate yield predictions for bifacial PV systems become more and more important. As the energy yield of bifacial PV systems depend on many different factors, especially on the rear-side irradiance, its energy yield is not as simple to model as for monofacial systems. This study compares two methods, view factor and ray-tracing, for bifacial PV system performance simulation. The commercial tool PVsyst is chosen to check the view factor method and the Fraunhofer ISE's inhouse developed tool is used to evaluate the ray-tracing method.

The view factor method shows mostly smaller rear-side irradiance in comparison with the ray-tracing method, while front-side irradiance shows a difference of 2~3% between the two models. The difference between two models in rear-side irradiance can vary up to 17.6% in RMSE and 17.7% in MBE

The albedo value for both systems should be more precisely measured in order to apply the correct input albedo value in simulation. The deviation from spectral mismatch and from the different climate should be as well considered. As the albedo is one of the most critical parameters for bifacial PV yield prediction, this step should be improved in order to improve bifacial PV yield simulation in general. Besides, DC and AC power comparison for both tools with long-term yield monitoring data from various climates should be evaluated.

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