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Simulation of the irradiance and yield calculation of bifacial PV systems in the USA and Germany by combining ray tracing and view factor model

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Abstract. Compared to conventional photovoltaic (PV), there are more influencing factors in bifacial photovoltaics to be considered to calculate incoming irradiance and energy yield. Accurate models to investigate the influences of the elevation, the albedo of the ground, the shading conditions between the PV rows and many other rear-side related factors are required. This paper combines the ray tracing (RT) and view factor (VF) models to calculate the irradiance with a subsequent electrical yield calculation using the one-diode model. To verify the results of the developed open-source simulation program BifacialSimu, accurate data from a plant in Golden, USA (single-axis tracked) and a commercially operated plant in Germany (fixed-tilt) are used. Through comparisons to the actual data, it can be concluded that a combination of RT and VF models seems to be valid for longer simulation periods with several months since the relative errors balance out. The RT-only simulation accurately reproduces the precise hourly radiation and electrical yield pattern. Still, a continuous positive deviation was found, which does not even out over long periods and is thus less accurate than the VF/RT combination. A simulation for a single month with RT can take several hours. Thus, the best simulation mode results according to user requirements.

Keywords: Solar energy / photovoltaic systems / bifacial photovoltaic / ray tracing / view factors

1 Introduction

Bifacial photovoltaics are becoming increasingly important in the PV industry [1]. The behaviour of these modules is analysed in numerous field studies. In addition, several commercial and freely available simulation programmes are already available on the market. Compared to monofacial PV, bifacial PV provides up to 30% more yield on the same area for fixed-angle generators. With tracked systems, up to 40% additional yield can be achieved. As a result, PV systems with bifacial modules can achieve the lowest possible Levelized Cost of Electricity (LCOE) [2]. Detailed and accurate simulation programmes are necessary to consider all aspects of the irradiance and yield calculation during the planning of these systems [2]. In addition, daily yield forecasts play a significant role in the direct marketing of PV electricity, where incorrect forecasts can lead to losses. The elevation height, the albedo of the ground, and other properties significantly affect the rear irradiance and thus the additional yield of bifacial PV systems [3]. The contribution of this scientific publication is the combination of two different irradiance simulation models. The simulation models are the Python libraries bifacial_radiance [4] of the National Renewable Energy Laboratory (NREL) and pvfactors [5] of SunPower Corporation. The two models are based on different radiation calculation models, one is the "ray tracing" model, and the other is the "view factor" model. The program (BifacialSimu [6]) is freely accessible and user-friendly. BifacialSimu is the only open-source bifacial simulation software that combines the two radiation models leading to the most accurate forecast: VF for the front side and RT for the rear side [7]. For the validation of the simulation program, actual radiation and yield data of two different plants are available. The plants are located in the USA and in Germany. The actual data of these plants will be compared with the simulation data and analysed for deviations. This paper can confirm that the combination of VF and RT is the most accurate forecast for long-term simulations.

2 Structure of BifacialSimu

The program structure can be divided into five different scripts. The subdivision into different scripts makes the program easier to understand, and a faster error search is

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Table 1. All the simulation modes for the irradiance simulation of the bifacial PV plant.

Mode 1	View Factor model for irradiance simulation of the front side and Ray Tracing model for irradiance simulation of the backside
Mode 2	View Factor model for front and back irradiance simulation
Mode 3	Ray Tracing model for front and back irradiance simulation

possible. The script with which the simulation is started is the main script. In the main script, all variables are declared, which are necessary for the simulation. In addition, different simulation modes can be set. Altogether there are three simulation modes, listed in Table 1. BifacialSimu [6] is divided into three main sections: irradiance simulation, albedo simulation and electrical simulation. In every sector a choice between different calculation methodologies is possible, like shown in Figure 1.

The simulation mode is then queried in the simulation controller (SC). The SC calls the data handler (DH) to initiate the simulation. In the DH, a path can be assigned where the weather file is stored. The weather file is read in and stored in a data frame. Furthermore, the SC accesses the radiation handler (RH). The RH then uses the weather data from the DH to run the irradiance simulation while considering the simulation mode. Either an RT simulation (bifacial_radiance) or a VF simulation (pvfactors) is run. Both libraries access pvlib for single-axis tracking (SAT). In the case of simulation mode 2, an irradiance report file is created by combining both reports from bifacial_radiance and pvfactors. This data is stored in a data frame and subsequently called in the calculation handler (CH). After all the irradiance data is acquired, the SC calls the CH to initiate the electrical simulation and generate an electrical simulation report. This simulation report is output in a comma-separated-value (CSV) file with all the relevant data for evaluating the results.

3 Simulation

The procedure for running a simulation is briefly explained below. First, the simulation variables must be entered via the main script. The simulation variables are defined in Table 2 and the module variables in Table 3. The simulation mode, the orientation of the modules, the height of the modules, the electrical module parameters and other essential parameters can be set via variables.

The weather data must be read in as CSV-format. Here the content must correspond to the TMY3 data format [8]. The global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI), direct normal irradiance (DNI), ambient temperature and albedo must be included as hourly values for the period under consideration. If the hourly albedo is not available in the weather data, a constant albedo of the subsurface can be specified in the variable declaration. If the albedo is defined as a variable, it will be read from the weather file.

If all inputs are defined, the simulation can be started. To represent the inhomogeneity of the radiation, especially on the rearside of the modules, the modules are divided into horizontal segments in both models. These segments divide the module on the Y-axis and can be analysed separately in the simulation. The results of the irradiance calculations are passed to the DH via the SC, which merges and exports them from the formats of the two irradiance simulation libraries into a unified format. Lastly, the electrical yields are saved in a CSV file stored at a specified destination path.

4 Calculation methodology

The calculation can be logically divided into the irradiance calculation, the electrical simulation and the yield calculation. The program's structure is reflected in this methodology as shown in Figure 1 and shortly described in Section 2. The irradiance calculation is conducted using the VF and RT models, while the electrical simulation uses the one-diode model. The one-diode model needs electrical parameters measured on the front and on the rear side of the bifacial PV module [9]. In case this data is not available, a simplified one-diode model [10] is used, which calculates the electrical rear side parameters using the bifaciality factor.

4.1 Irradiance calculation

The two libraries, bifacial_radiance [4] and pvfactors [5], are used for the irradiance simulation. bifacial_radiance creates a three-dimensional model of the hourly conditions in the year on the geometries entered. These three-dimensional models are then used to simulate the irradiance with ray tracing. pvfactors, on the other hand, simulate the irradiance via view factors and create a two-dimensional model. In pvfactors, the pvlib Python implementation of the Perez Model [11] is used [5]. For combining both computational methods within a simulation, some simplifications are used, which will be subsequently explained. While bifacial_radiance offers the possibility to specify geometries with gaps and spaces up to the cell level, pvfactors accounts for modules as an area. Therefore, this function of bifacial_radiance is not used in BifacialSimu. Also, more complex arrangements of modules with different orientations or different numbers of modules in each row and back shading caused by the mounting system cannot be considered within the simulation. Both libraries require a sun position calculation and

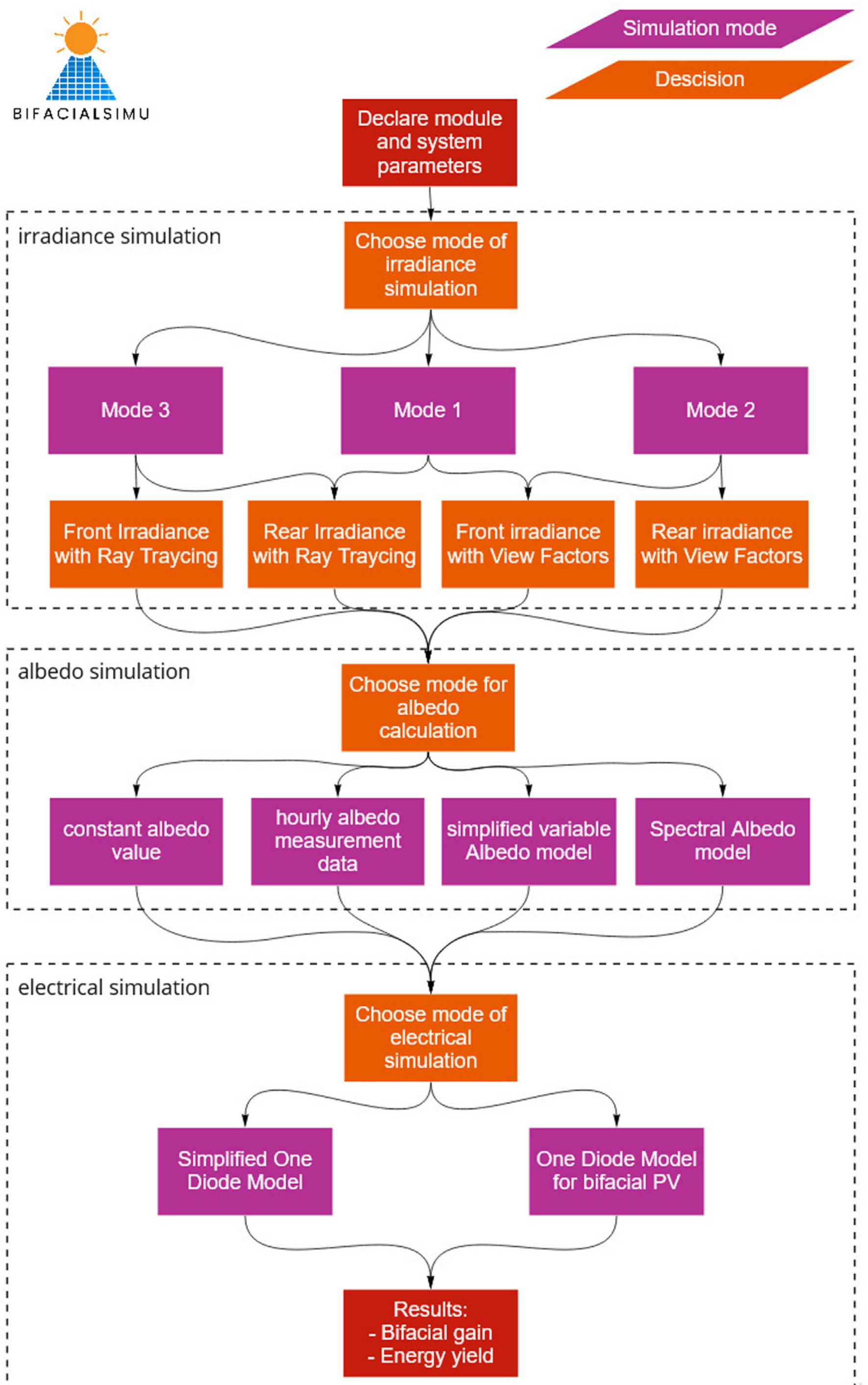

Fig. 1. The simulation procedure can be divided into 3 different parts. The irradiance simulation defines the calculation method for front and rear side of the PV module and uses either VF, RT or both. The albedo simulation can be conducted using a simplified variable Albedo model or a Spectral Albedo model approach. The user can also define a constant albedo value or implement albedo measurements into the simulation. Finally, the electrical simulation calculates energy yield and bifacial gain of the PV plant using either a simplified One Diode model or a One Diode model specifically tailored to bifacial PV.

Table 2. Most of the relevant data concerning the bifacial PV simulation. Here, the user can define usual characteristics of PV power plants like number of rows and modules per row.

SimulationDict	Dictionary containing important simulation parameter
WeatherFile	Weather file in TMY format
Tilt	Tilt of the PV surface [deg]
Hub_height	Height of the rotation axis of the tracker [m]
Azimuth	Azimuth of the PV surface [deg] 90°: East, 135° : South-East, 180°:South
nMods	Number of modules
nRows	Number of rows
Moduley	Length of modules in y-axis
Modulex	Length of modules in x-axis
Albedo	Measured albedo average value
FrontReflect	Front surface reflectivity of PV rows
BackReflect	Back surface reflectivity of PV rows
Longitude	Longitude of the simulation site
Latitude	Latitude of the simulation site
Gcr	Ground coverage ratio (Module area/land use)
Module_type	Name of the module

Table 3. The module dictionary encompasses all the relevant data of the bifacial PV module, which is relevant for the electrical simulation. In case that there is no rear module data specified by the manufacturer, a simplified electrical simulation approach may be applied instead.

ModuleDict	Dictionary containing important module parameter
bi_factor	Bifaciality factor
n_factor	Module efficiency
I_sc_f	Short-circuit current measured for front side illumination of the module at STC [A]
I_sc_r	Short-circuit current measured for rear side illumination of the module at STC [A]
V_oc_f	Open-circuit voltage measured for front side illumination of module at STC [V]
V_oc_r	Open-circuit voltage measured for rear side illumination of module at STC [V]
V_mpp_f	Front Maximum Power Point Voltage [V]
V_mpp_r	Rear Maximum Power Point Voltage [V]
I_mpp_f	Front Maximum Power Point Current [A]
I_mpp_r	Rear Maximum Power Point Current [A]
P_mpp	Power at maximum power Point [W]
T_koeff_P	Temperature coefficient [1/°C]
T_amb	Ambient temperature for measuring the temperature coefficient [°C]
T_koeff_I	Temperature coefficient for I_sc [1/°C]
T_koeff_V	Temperature coefficient for U_oc [1/°C]
zeta	Irradiance coefficient for open circuit voltage [–]

calculation of the module inclination angles [5,12]. To speed up the simulation, these calculations are performed only once via bifacial_radiance, which performs this calculation via pvlib [12]. The results of the calculations are then transferred to pvfactors in the form of a data frame.

The simulation mode cumulative sky of bifacial_radiance has limited use in this simulation. The mode accumulates all sky states over the considered period for the irradiance simulation. Only a single value of the total irradiance over the considered period can be calculated.

4.2 Electrical simulation

The simulation of the electrical energy yield of the bifacial PV system is performed using the one-diode model. Bifacial values for fill factor FF_b, short-circuit current I_{SC_b}, and open-circuit voltage V_{OC_b} are first calculated using the module parameters from the datasheet of the modules. Then, the power P_{MPP} of the whole module is calculated by equation (1) [1].

$$P_{MPP} = FF_b{\cdot}V_{OC_b}{\cdot}I_{SC_b}. \tag{1}$$

If no specific values for the front and rear side of the modules are available, a simplified electrical simulation can also be carried out. Here, the rear side power of the solar modules is determined via the bifacial factor (BF). A fill factor FF_{rear} is calculated for the back surface based on the BF. This FF_{rear} is then used in the power calculation for the backside. The powers of the front and rear sides are afterwards added together.

4.3 Yield calculation

The electrical energy yield of the PV system is calculated using electrical power. Since power values are calculated hourly, they can be equated with electrical energy. The total hourly electric energy yield Y_{bh} [Wh] for the system is calculated by summing up the hourly energy yields for each row. The yield of a row is obtained using the average hourly power output of a representative module in a row, multiplied by the number of modules in a row. The area-specific electrical energy yield Y_b is used in the evaluation, which is the quotient of the total hourly energy yield Y_{bh} of the system and the total area A_{module} [m^2] of the solar modules (Eq. (2)).

$$Y_b = \frac{Y_{bh}}{A_{module}}. \tag{2}$$

5 Validation and evaluation

In the following, the simulation results for both plants under consideration are validated using actual data and examined for deviations. Therefore, the measured front irradiance and the yields of two plants at two different locations are compared with the simulation results. There are no measured data for the back irradiance in both cases, which can not be compared directly with the simulation data. NREL operates the plant in the USA at the site in Golden, USA [13]. Here, measurement data of the DC yield of module Y_b, albedo, irradiance onto the front side of the modules Irr_{front}, GHI, DNI, DHI and ambient temperature are available in an hourly resolution and high data quality. Data of the second row from the dataset is used as a reference. The module row consists of 19 modules, which are connected in series. This plant uses single-axis tracking. A backtracking algorithm is used, where the trackers correct for self-shading, when following the sun at high zenith angles during the sunrise and sunset [14]. The modules are oriented to the south, and the axis of rotation is at the height of 1.5 m. In addition, data from a nearby weather station of the NREL Solar Radiation Research Laboratory (SRRL) are available [15]. Unrealistic measured data, such as negative radiation or missing values, are filtered before comparison. In case of missing values, values from the previous hour are used. The module parameters needed to simulate the electrical yield are taken from [16]. The rated power of the modules is approximately 350 Wp. The modules are poly-p type PERC modules. A period of seven winter month between 01.10.2019 and 30.04.2020 is considered for simulation due to the completeness and quality of the measurement data in this period. Since the period is mostly in times with low solar declination, it can only represent those months and not a full year. Plant Germany is operated in Niedersachsen, Germany. Hourly AC yield data and irradiance on the front side of the modules are available here. The yield data are grid feed-in values, so inverter losses, interconnection losses, and line losses are already included. This must be considered when evaluating the data. Only percentage deviations between measured data and simulation data and the annual yield, can be presented in this paper. The plant has a nominal output of 744.8 kWp. The modules used are 380 Wp modules STP380S-72/Pfh+ from the Suntech Power company. The modules use a fixed tilt. The radiation and weather data, GHI, DHI, DNI and the ambient temperature required for the simulation are obtained from the German Weather Service (DWD) nearby. The measured data are prepared to be read into the program. A period of one year between 01.05.2020 and 30.04.2021 is considered.

Table 4. Most important simulation parameters for the bifacial PV system simulation.

Azimuth angle	180° = South
Tilt angle of PV surface	10°
Tracking limit angle	60°
Height of the rotation axis of the tracker	1.3 m
Albedo	0.26
Front reflectivity	0.03
Back reflectivity	0.05
Ground coverage ratio (module area/land use)	0.35

5.1 Evaluation of the results of plant USA

In the following, the accuracy of the simulation results is evaluated based on the actual data described for Plant USA. The four simulations considered have different simulation durations, which differ significantly between simulation modes. While the simulations (Tab. 4) in mode 1 with fixed and variable albedo require 8:28 h and 9:08 h, the PC used in mode 3 with fixed and variable albedo requires 12:43 h and 14:53 h, respectively. Mode 2 does not use ray tracing and therefore only requires between 2 and 4 minutes for the simulations. Figure 2 shows the relative deviation of the simulation results (Irr_{front}, Y_b) from the actual data in each month. In addition, the difference between mode 1, mode 2 and mode 3 with constant albedo is shown in the graph.

The simulation results of mode 1 deviate from the measured data by 19% in December. This is the most substantial positive deviation for the irradiance on the module surface and the electrical yield. For mode 1, the irradiance with −10% in March and −16% in April and

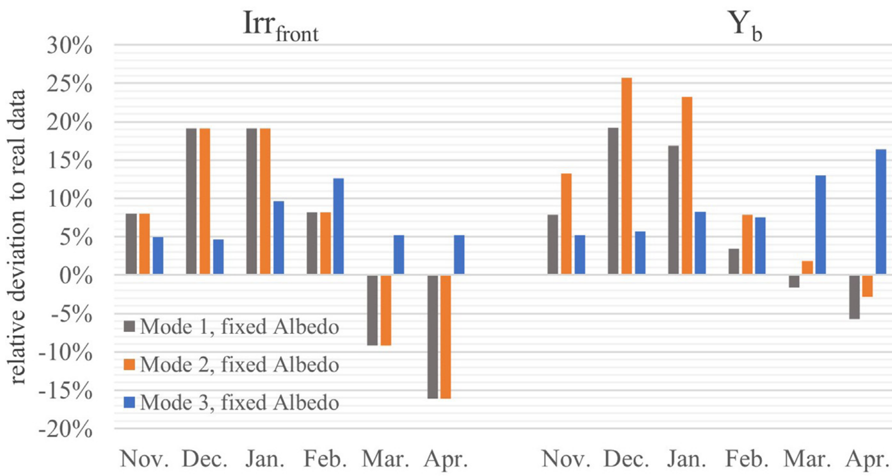

Fig. 2. The figure shows the relative deviation between simulation data and measured data of the front irradiance Irr_{front} and the area-specific energy yield Y_b in the time frame of November 2019 to April 2020. Mode 1 and 2, which use VF for front side irradiance calculation, show the same results for Irr_{front}. The largest positive deviation is 19% in December and the largest negative difference is −16% in April. Mode 3, which uses RT, shows only positive deviations. The front irradiance deviations also translate over to the energy yield Y_b. Here mode 2, which uses only VF, calculates the highest deviations between simulation and measured data. The influence of RT for the calculation of the rear irradiance can be seen in the lower deviations of mode 1. The pure RT simulation mode 3 only produces positive deviations, which are highest in April with 16%.

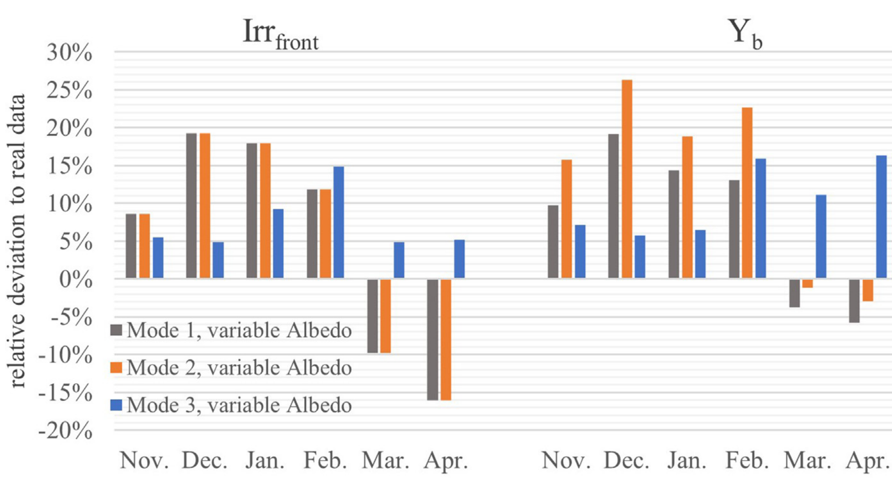

Fig. 3. This figure represents the simulation data using a variable albedo. The data shows a similar behaviour to the simulation using a fixed albedo. The deviation between variable albedo and fixed albedo is strongest in February, where mode 1 deviates 12% from the real data, whereas constant albedo only shows a 8% difference. This maximum deviation is also transferred over to the energy yield, where the delta is 10% between the 3% and 13% deviation to measurement data for fixed and variable albedo respectively. The deviation for front irradiance simulation using variable albedo is smaller in other months, with negatives cancelling out positive values over the simulation time-frame, resulting in an average deviation of 0.9% for mode 1.

the electrical yield with −4% in March and −6% in April are calculated too low. Mode 2 behaves the same as mode 1 due to the same calculation methodology for the front side, but the calculated back side irradiance influences the electrical yield with VF. The simulation deviates even more from the measured data in the first three months, but the deviation is the smallest of all modes in the spring months. Mode 3 consistently has a positive deviation of at least 5.2% for irradiance and electrical yield. The most significant positive deviation is in April with 16%.

The difference between fixed and variable albedo is particularly strong in February, as can be seen in Figure 3. Here, the simulation results for mode 1, fixed albedo, deviate by 8% from the actual data, whereas the deviation is 12% for a variable albedo. This deviation is then also transferred to the electrical yield. Here the difference between variable and constant albedo is 10%, where the deviation from the actual data is 3% and 13%, respectively. The difference between the fixed and variable albedo simulations is slight in the other months, resulting in an

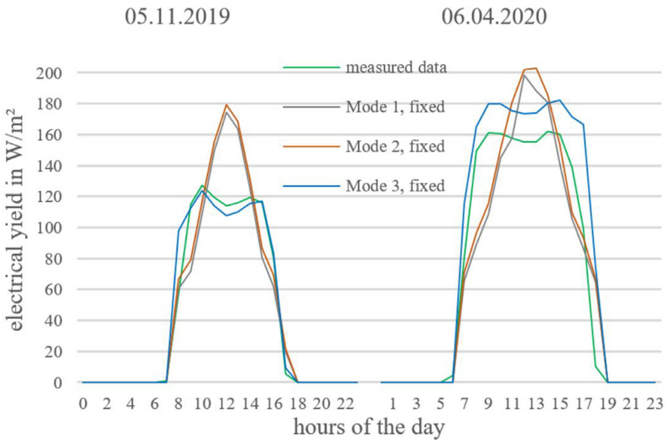

Fig. 4. The figure compares the electrical yield of measured data to the simulation data on the days 05.11.2019 and 06.04.2020. Simulation mode 3 (RT) follows the measured data closely over the course of the day. Small deviations can be found, which may be attributed to the lack of consideration of mismatching losses. The overall relative deviation is −6.5%. The VF based simulation Mode 1 and 2 show a different trend, with a peak in midday hours and negative deviations in morning and evening hours. This development resembles the course of GHI over the day. The purely VF based simulation mode 2 produces consistently higher energy yields than the VF/RT combination mode 1.

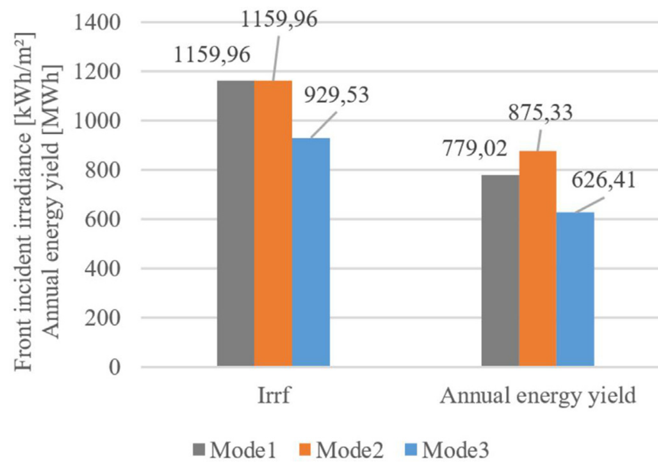

Fig. 5. The figure illustrates front irradiance and annual energy yield for simulations on plant Germany. Comparisons to the measured front irradiance and energy yield can be made, but exact values cannot be disclosed in this article. The simulated values of modes 1 and 2 are identical due to being calculated using VF and both are close to the measured front irradiance. mode 3 with RT based calculations shows a larger deviation. For the energy yield, mode 1 is closest to the measured data, whereas mode 3 shows a significant negative deviation to the real data.

average deviation between the irradiance results of 0.6% to 0.9% and between the electrical yields of 4.4% to 5.2%. Mode 3 simulates the actual course of the electrical energy yield of the plant qualitatively better. This can be seen in Figure 4. Here two selected daily courses of the simulated and measured electrical energy yield are shown. On the left side of the diagram the 05.11.2019 and on the right side the 06.04.2020 are shown. On 05.11.2019, it can be seen that the energy yield simulated with modes 1 and 2 exceeds the actual yield between 10 am and 2 pm. The simulated yield has a peak of 170 $\mathrm{W/m^2}$ there, which is not present in the actual data.

Mode 3 follows the measured yield closely and the deviations are minor. They can also be attributed to the lack of consideration of mismatching. At noon, the measured yield is 114 $\mathrm{W/m^2}$ and the simulated 107 $\mathrm{W/m^2}$, which corresponds to a relative deviation of −6.5%. On 06.04.2020, it can be seen that the electrical yield of the VF calculation is significantly below the actual data in the morning and evening hours and above it in the midday hours. Overall, mode 3 represents the profile of actual electrical yields more closely. A similar observation can be made on the 05.11.2019. Analyzing the underlying irradiation data, these days had strong direct and low diffuse share. Since Mode 1 and Mode 2 are calculated with VF and Mode 3 entirely with RT, it can be said that daily characteristic curves on sunny days are approximated better using RT.

The module array's total measured electrical energy yield between November and April is approximately 148 $\mathrm{kWh/m^2}$. These are DC values, so inverter and cable losses are not yet included. Despite the significantly higher relative deviation of the simulation results from the measured values in mode 1, the irradiance on the front of the modules and the total electrical yield is closer to the measured data over the entire period under consideration. The deviation of the total electrical yield is 4.4% for mode 1, 8% for mode 2 and 10.4% for mode 3 (fixed albedo). As can be seen in Figure 5, mode 1 is more accurate in the total consideration because negative and positive values balance each other out. This mechanism does not affect mode 2 as strongly and mode 3 not at all.

5.2 Evaluation of the results of plant Germany

In the following, the accuracy of the simulation results for plant Germany is evaluated with the previously described actual data. Only the irradiance on the front side and the simulated DC yield are compared since these are the only real datasets available. The exact values for the deviations cannot be disclosed in this paper. The albedo used for the simulation is 0.26, which is the average albedo at the site. Additional parameters are displayed in Table 4. The simulations considered took a long time to complete. A simulation in mode 1 needed 52:46 h, mode 3 took 88:20 h, whereas mode 2 was the fastest, with only 2 minutes simulation time on a regular computer with 16GB RAM. All modes simulated the plant for a whole year. The results, in Figure 3, show that the front side irradiance values (Irr_f) of mode 1 and mode 2 are identical since VF calculates the front side irradiance in both modes. The simulated values are only slightly below the actual measured data in this case. In mode 3, in which RT is used to calculate the radiation of the front side, the deviation from the measured data is higher, so the simulated values are even lower than modes 1 and 2. Since the weather data used for the simulation is a TRY of the observation period 1995–2012, certain deviations between simulation and actual data are expected. According to a weather map of the DWD, the global radiation of 2020 in the region can deviate from the TRY by up to 15% [17]. Comparing the electrical yield between the three simulation modes and the actual data gives similar results to the irradiance simulation. A medium deviation in the annual energy yield is obtained for the mode 1 and mode 2 simulations. Here, mode 2 is higher than the actual data, and mode 1 is lower. Mode 3, on the other hand, results in a significantly lower annual yield than the actual data. Overall, mode 1 is closest to the measured energy yield.

6 Error consideration and conclusion

In the simulations, loss mechanisms such as soiling, mismatching and interconnection losses are not considered. In addition, the entire module area is assumed to be the absorbing area, which is likely to be smaller in reality due to the edges of the modules, junction boxes and gaps between the cells. Also, shading effects from the mounting system on the rear side are not considered. These neglected effects should lead to a positive deviation from the presented simulation results. This is the case for the simulation with mode 3 of the Plant USA, where the relative deviations in irradiance and yield are positive every month. Therefore, this is an indication that the results of the RT simulation are more in line with the actual data. In theory, the simulation results of Plant Germany should also deviate positively overall. In addition to the effects already described here, DC yields from the simulations are compared with AC yields from the actual data and conversion losses from DC to AC voltage are not factored in the calculations. In the simulations, static reflection losses of 3% on the front side and 5% on the backside are assumed. These angle-dependent losses would have to be considered for a more detailed analysis.

In summary, it can be said that the combination of the two calculation models VF and RT provides more accurate results for the cumulative electrical yield and the irradiance on the module surface for a half-year or year-round simulation. Positive and negative deviations in the combined VF/RT simulation tend to balance out, but this is not the case with the pure RT simulation. On the other hand, the RT simulation more clearly reproduces the actual course of the irradiance and thus of the electrical yield. Still, the permanently positive deviation does not balance out over more extended periods, resulting in a more significant deviation for several months. The pure view factor calculation was the least accurate in the day-by-day view and had higher deviations when viewed over a more extended period than the combination of VF and RT. As a result, the combination of the two calculation models is suitable for yield prediction over longer periods and thus can be applied in PV system design. However, the RT model should be superior when forecasting electrical yields for intraday energy trading.

Author contribution statement

E.-M. Grommes designed the model and the computational framework. F. Schemann, F. Klag and S. Nows further developed the model and carried out the validation. U. Blieske and E.-M. Grommes conceived the study and were in charge of overall direction and planning. E.-M. Grommes and F. Schemann wrote the manuscript with input from all authors.

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