frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 04 March 2025
DOI 10.3389/fenrg.2025.1527681



# Towards precision in bifacial photovoltaic system simulation: a model selection approach with validation

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RECEIVED 13 November 2024
ACCEPTED 06 February 2025
PUBLISHED 04 March 2025

CITATION
Grommes E-M, Koch M, Hadji-Minaglou J-R, Voos H and Blieske U (2025) Towards precision in bifacial photovoltaic system simulation: a model selection approach with validation.
*Front. Energy Res.* 13:1527681.
doi: 10.3389/fenrg.2025.1527681



As global reliance on sustainable energy solutions intensifies, there is a growing need to optimise and accurately predict renewable energy outputs. Bifacial photovoltaic systems, which are capable of capturing irradiance on both their front and rear sides, represent a significant advancement over traditional monofacial systems, yielding higher energy per area. The accuracy of simulation models for these systems has a direct impact on their financial viability, necessitating the use of comprehensive and reliable simulation frameworks. This research validates BifacialSimu, an open-source simulation tool designed to enhance the prediction of bifacial PV system energy outputs by incorporating multiple simulation models. The practical validation of BifacialSimu is based on empirical data from three diverse geographic locations. The locations of Golden, United States; Heggelbach, Germany; and Florianópolis, Brazil, provide insights into the performance of bifacial PV systems across a range of environmental conditions and installation configurations. These findings underscore the practical applicability of BifacialSimu, with recommendations for simulation model selection and methodological advancements, paving the way for more precise and efficient bifacial PV system simulations across diverse scenarios. This study employs a number of validation metrics, including relative error, coefficient of determination and Normalized Root Mean Square Error, to assess the accuracy of the simulations. The findings indicate that the Ray tracing method is the most accurate of the irradiance simulation modes for most scenarios. The validation results highlight that the Ray Tracing method achieves superior accuracy in irradiance simulations, particularly under varied environmental conditions, while Variable Albedo models further enhance predictive precision by accounting for dynamic factors such as snow cover.

KEYWORDS

**photovoltaic, bifacial photovoltaic (bPV), simulation, solar energy, irradiance, albedo**

## 1 Introduction

As the world increasingly turns towards sustainable energy solutions, the optimisation and accurate prediction of renewable energy outputs have become of paramount importance. Among the various technologies currently under investigation, bifacial photovoltaic (PV) systems stand out for their potential to harness solar energy in a more efficient manner than traditional monofacial systems. By capturing sunlight on both the front and rear sides, bifacial PV systems offer higher energy yields per area. It is imperative that simulation models achieve the highest possible level of accuracy, as their credibility directly impacts the financial viability of bifacial PV projects. The complexity of these systems, with a multitude of variables ranging from incident light angles, row spacing, table height to ground reflectivity, demands a comprehensive and reliable simulation framework. In this context, our research introduces and validates BifacialSimu, an open-source simulation tool designed to refine the prediction of energy outputs by accounting for a variety of factors influencing bifacial PV performance by incorporating several simulation models for the user to choose from.

The practical validation of BifacialSimu is central to our approach, which is based on the comprehensive analysis of empirical data from three geographic locations: Golden, United States; Heggelbach, Germany; and Florianòpolis, Brazil. Each site provides unique insights into the behaviour of bifacial PV installations, reflecting a broad spectrum of environmental conditions and installation configurations. This comparison examines the accuracy of the software across a range of operational scenarios. It forms the basis for a simulation model recommendation for the simulation of large-scale bifacial PV systems.

The adaptation of monofacial PV performance models to simulate bifacial modules by introducing irradiance bifacial gain has yielded favourable outcomes, with analytical models demonstrating superior performance compared to empirical models in considering bifaciality (Bouchakour et al., 2020). Furthermore, the combination of ray tracing and view factor models for irradiance calculation, along with electrical yield calculation, has been demonstrated to be an effective approach for long-term simulations (Grommes et al., 2023). However, it should be noted that the various simulation models require different inputs, have varying simulation times, and produce disparate exact results. The presented tool, BifacialSimu, offers the flexibility to select between different models, thereby enabling its use in a range of scenarios.

The methodology used for validation utilises several metrics, including relative error for annual energy yield, the coefficient of determination ($R^2$) for hourly outputs, and the Normalized Root Mean Square Error (*NRMSE*) as well as the Relative Error (*RE*) for average deviations. These quantitative measures provide a solid foundation for assessing the reliability of simulation results, offering insights for further refining bifacial PV simulation.

The paper begins with an explanation of the simulation algorithm and its implementation in BifacialSimu, before progressing to a validation process that leverages data from three diverse installations. The objective of this approach is to make a significant contribution to the advancement of bifacial PV technology, with the ultimate goal of achieving greater accuracy and reliability in solar energy prediction. Furthermore, recommendations are provided to select the most suitable model combination for different simulation scenarios.

# 2 Methodology

## 2.1 Validation approach

The validation approach for *BifacialSimu* meticulously encompasses a comprehensive period during which all irradiance simulation modes are applied and rigorously compared to ascertain their accuracy and suitability for different application scenarios. This phase of validation integrates the *Parameter Variation Analysis*, where the impact of various simulation parameters is explored to determine their influence on model precision. Key variables such as albedo data (captured hourly or averaged), different electrical configurations, weather data inputs (auto-downloaded versus measured), and distinct methods within the ray tracing module are systematically varied. That not only offers insights into the software's flexibility and robustness under diverse operational conditions but also assists in identifying which irradiance simulation mode is optimally tailored for specific application cases, thereby facilitating a targeted approach in photovoltaic simulation practices.

The utilised validation metrics are essential for quantifying the software's precision and dependability. These include the relative error for annual energy yield predictions, the coefficient of determination ($R^2$) for consistency of hourly outputs, and the NRMSE for assessing average deviations in hourly simulations. Each metric contributes to a holistic evaluation of the simulation's accuracy, providing a robust framework for ongoing development and refinement of *BifacialSimu*.

## 2.2 Validation data

The validation is based on empirical data from three sites. Golden, United States; Heggelbach, Germany; and Florianopolis, Brazil. In the Golden, United States installation, the *Bifacial Experimental Single-Axis Tracking Field* (BEST Field), operated by the *National Renewable Energy Laboratory* (NREL), is designed to assess the performance of five bifacial PV module technologies relative to their monofacial counterparts. Initiated in 2019, the facility features 10 rows with 20 modules, each and a total capacity of 75 kWp. These modules are mounted on single-axis trackers that incorporate a backtracking algorithm to optimize solar absorption and reduce shading between rows.

Instrumentation at the BEST Field is extensive and strategically placed to monitor both incident and reflected solar radiation on the front and rear of the modules across different array positions. Key parameters recorded include module temperature, ground albedo, and net energy production. Regular ground maintenance is performed to ensure consistent site conditions, which may influence module reflectivity and performance.

Approximately 100 m from the array, the *Solar Radiation Research Laboratory* (SRRL) station provides vital meteorological data, such as *Global Horizontal Irradiance* (GHI), *Direct Normal Irradiance* (DNIr), and *Diffuse Horizontal Irradiance* (DHIr). The albedo is measured at the SRRL and at the module site.

Data collection is handled with a temporal resolution of 1 min, focusing primarily on the second row of the installation. This row includes 19 modules (due to one being used exclusively for data recording at the cell-string level), cumulatively generating 6.84 kWp.

Data processing scripts aggregate energy yields hourly from minute-level measurements, with adjustments made for albedo, irradiance, and temperature inconsistencies using data from the SRRL station when necessary. For in-depth analysis, the 2021 data was selected as it provides the most complete dataset.

At the Heggelbach installation in Germany, the *Agricultural Photovoltaic* (Agri-PV) system uniquely combines photovoltaic technology with agricultural production. Commissioned in 2016, this pioneering project involves the collaboration of various stakeholders, including *Fraunhofer ISE* and *BayWa* r.e., and utilises an installed capacity of approximately 194.4 kWp on solar modules that are elevated 6 m above the ground to optimise the dual use of land for both energy production and crop cultivation.

The facility's geographical positioning on a southwest-facing slope introduces unique challenges in replicating topographical nuances within the simulation framework, potentially impacting the accuracy of simulation outcomes. Data for this analysis, sourced from the project partners, spans from 2017 to 2022 and is processed with a temporal resolution of 5 min. In the absence of specific albedo data, a standard value representative of the installation's ground surface—predominantly grass and crops—is assumed for accurate simulation reflections (24% Betts and Ball, 1997).

The 2022 data, offering the most complete dataset, was chosen for in-depth analysis. Anomalies, such as the unexpected decrease in bifacial yield observed in December, are noted and factored into the validation process, underscoring potential measurement inaccuracies and assumptions.

Located in Florianópolis, Brazil, the *Solar Systems Laboratory at the Federal University of Santa Catarina* (UFSC), in collaboration with *CTG-Brazil*, focuses on evaluating the performance of bifacial photovoltaic modules across various ground surfaces. Since its initiation on 1 August 2022, the facility has been instrumental in studying the operational dynamics of both fixed and single-axis tracking photovoltaic systems.

The installation includes several key configurations: four rows of bifacial silicon modules each set on different surfaces—white gravel, kaolin, sand, and grey gravel—all equipped with single-axis trackers to optimize sun exposure throughout the day. The peak power output of each row is 16.8 kWp. Additionally, there is a row of cadmium telluride modules on grey gravel, also with tracking capability, and two rows of fixed tilt silicon modules on grey gravel, serving as a comparative baseline.

The albedo data is recorded at a distance of approximately 20 m from the system setup by a dedicated albedo station. This station has a grey gravel ground, which is why the single-axis tracking and fixed tilt setups with grey gravel are selected for analysis.

For this study, the period from 2 November 2022, to 31 December 2022, was specifically chosen due to its consistency in data quality, avoiding any interruptions caused by maintenance or severe weather conditions that occurred earlier in the year. During this time, data were collected at 1-s intervals and then averaged into 1-min increments for storage. A dedicated script further aggregated this data hourly to align with simulation requirements.

The datasets for all sites provide records for GHI, DHI, DNI, front side radiation, back side radiation, albedo (except Germany), ambient temperature, module temperature and bifacial power. In order to facilitate the comparison with the simulation, bifacial power per square meter is calculated from bifacial power and module area. In order to ensure the integrity of the data set, any instances of inconsistent data points, such as negative values or anomalies, are excluded from all simulation-relevant data.

# 3 Simulation

## 3.1 Design of simulation algorithm

The simulation program *BifacialSimu* calculates the energy yield of a bifacial PV system. It is written in the python programming language and was published in 2022 in the Journal of Open Source Software (Grommes and Blieske, 2022). A Graphical User Interface (GUI) allows users to enter all the necessary input parameters and make settings (see Figure 1). The input parameters consist of weather data, module parameters, and simulation parameters. The weather data is read from a text file and must be available in hourly resolution for the desired simulation period, such as 1 year. Alternatively, a Typical Meteorological Year (TMY) can be generated and downloaded by entering the latitude and longitude of the simulation location. The weather data comprises of the date and time, Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNIr), Diffuse Horinzonal irradiance (DHIr), temperature, pressure, and preferably albedo. In addition to the input parameters, settings can also be made via the GUI. The PV system can be designed with or without single-axis tracking and backtracking. The simulation algorithm comprises three main parts: irradiance simulation, albedo simulation, and electrical yield simulation. The irradiance model offers three different calculation modes for front and back radiation. The python library *pvfactors* Anoma et al. (2017) is used for the View Factor (VF) method and the *NREL* library *bifacial_radiance* for the Ray Tracing (RT) method (PV Performance Modeling Collaborative PVMC, 2023):

- Mode 1: Calculation of front side radiation with VF and rear side with RT.
- Mode 2: Calculation of front and rear side radiation with VF.
- Mode 3: Calculation of front and rear side radiation with RT.

Albedo can be integrated in three different ways. One way is to select a constant albedo value from a database that is dependent on the material. The program currently stores 31 different materials and their corresponding empirical albedo values. Another way is to assume that the albedo is a time-varying value. In this case, the program uses hourly measurements stored in the weather file. If no measurements are present, the albedo can be calculated as variable albedo, which changes with the position of the sun, based on the albedo under direct and diffuse illumination (Ziar et al., 2020). The electrical model offers two variations of the one diode model. The first one relies on the electrical values from the module datasheet and the bifaciality of the module is considered with an irradiance ratio (Ortiz-Rivera and Peng, 2005). The second energy yield model requires electrical values for both the front and rear sides of the module, which may not be available for every module, but provides higher accuracy. The simulation results are saved in an output folder and include the calculated front and rear radiance and energy yields. Additionally, the weather file and the data frame containing the sun position calculation parameters, radiation data, temperature, air pressure, and albedo values are also output.

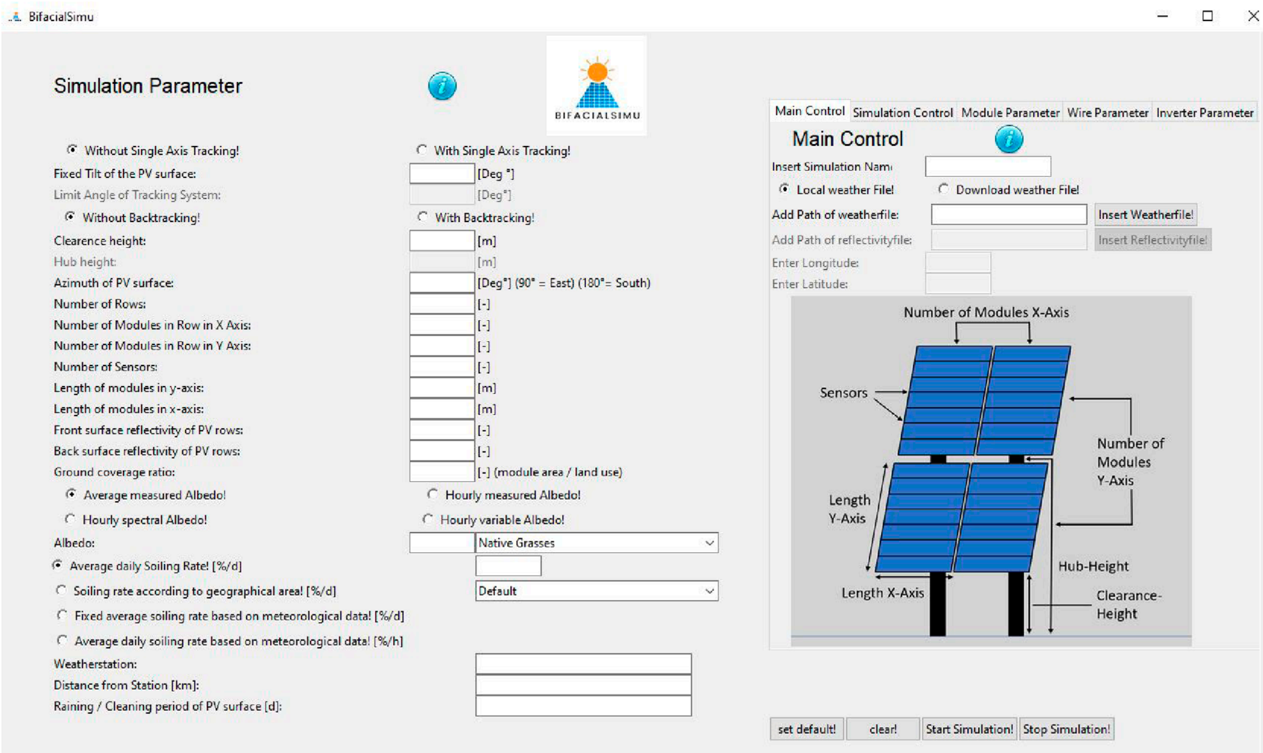


FIGURE 1
Graphical user interface of BifacialSimu.

## 3.2 Simulation models

This subchapter outlines the essential models utilised in the simulation of bifacial PV systems in *BifacialSimu*, elucidating the rationale behind their selection. The accurate replication of the sky's condition plays a critical role in simulating the solar irradiance incident on both the front and rear sides of bifacial modules. For longer-term simulations that require the aggregation of solar irradiance over extended periods (seasonal or annual), a cummulative sky model is applied (Robinson and Stone, 2004). The provision of cumulative sky conditions simplifies the simulation process for scenarios where detailed hourly changes are less critical, prioritising efficiency.

The variable albedo model Chiodetti et al. (2016) is a further example of a model that has been selected for its dynamic adjustment of albedo based on real-time solar positions and weather conditions, offering a detailed hour-by-hour account of ground reflectivity.

A simplified one-diode model? is utilized to simulate the electrical characteristics and performance of the bifacial modules. This model is selected for its efficacy in balancing comprehensive coverage of the key electrical parameters (including temperature and irradiance effects) with relative simplicity, obviating the need for complex or often unavailable bifacial-specific module data. By utilising datasheet specifications and adapting them through a simplified approach, this model facilitates broad applications under varying environmental conditions.

The simulation of irradiance received by bifacial modules, and the subsequent calculation of energy yield, utilises a combination of RT and VF methodologies, as described in chapter 3.1. That dual approach is chosen to optimise accuracy and computational efficiency. The VF methods provide a rapid estimation of direct and diffuse irradiance on the more uniformly exposed front side NREL (2023), while the RT Deline and Ayala (2017) methods are applied to the rear side to intricately model the effects of variable ground reflectivity and shading.

# 4 Validation and model selection

## 4.1 Validation

This section presents the empirical validation of the simulation results generated by *BifacialSimu*, utilising data from four systems across three different locations. Figure 2 presents the simulation outcomes for the fixed tilt configurations on a monthly basis, evaluated using three validation metrics: NRMSE, $R^2$, and RE. These metrics for the whole period are shown in Table 1 for the plant in Germany and in Table 2 for the fixed tilt system in Brazil.

The results indicate that RT emerges as the most accurate method across all considered metrics. The hourly performance of the bifacial systems is well captured by the RT method, as evidenced by a NRMSE and a high $R^2$. Additionally, the annual yield predicted by the RT method aligns closely with the actual measurements, with an average RE approaching zero. This indicates

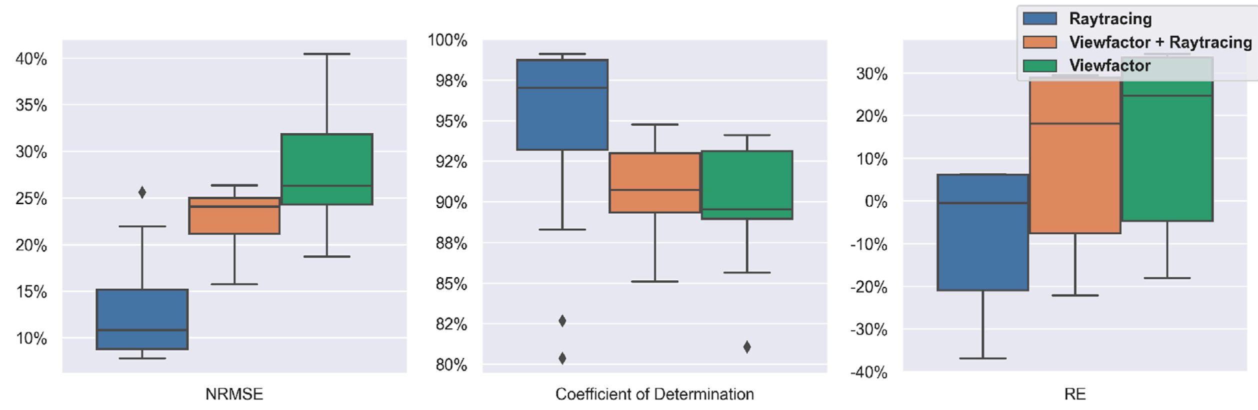


FIGURE 2
NRMSE and coefficient of determination for the fixed-tilt systems in Heggelbach, Germany and Florianopolis, Brazil.

TABLE 1 Simulation results - bifacial energy yield - Heggelbach 2022.

| Irradiance simulation | $R^2$ | RE | NRMSE |
|---|---|---|---|
| Raytracing | 94% | −19.2% | 18.4% |
| Viewfactor | 91% | 0.07% | 24.9% |
| Viewfactor + Raytracing | 91% | −4.8% | 23.3% |

TABLE 2 Simulation results - bifacial energy yield - Florianópolis 2022.

| Irradiance simulation | $R^2$ | RE | NRMSE |
|---|---|---|---|
| Raytracing | 99% | 6.1% | 7.8% |
| Viewfactor | 91% | 27.6% | 24.7% |
| Viewfactor + Raytracing | 92% | 23.4% | 23.2% |

a high fidelity in the replication of real-world conditions and system behaviour.

In contrast, the two VF methods exhibit less precise results compared to RT, particularly in terms of hourly performance and relative error. The hybrid approach, which combines VF and RT methodologies, achieves results that are very similar to those of the pure VF method. However, the hybrid method does show a slight improvement over the VF approach alone, specifically demonstrated by a reduction in NRMSE.

The validation metrics underscore the superiority of the RT method in accurately simulating bifacial PV system performance. The capacity of RT to capture both the dynamic hourly variations and the overall annual energy yield is of critical importance for the reliable long-term prediction and optimisation of bifacial PV systems. Despite the enhancements provided by the hybrid approach, the marginal improvements indicate that RT remains the benchmark for high-precision bifacial PV system simulations.

Figure 3 illustrates the three validation metrics for the single-axis tracking simulations on a monthly basis. Similar to the Fixed Tilt configurations, RT achieves the most accurate representation of the hourly performance, with an average NRMSE of 8% and an $R^2$ of 98%. This demonstrates RT's capability in accurately capturing the dynamic variations in bifacial PV system performance. The NRMSE, $R^2$ and RE for the whole period are shown in Table 3 for the plant in the United States and in Table 4 for the tracked system in Brazil.

In contrast, the results from the VF methods show a wide range of errors. For the simulations conducted for the system in Brazil, VF methods exhibit a high degree of accuracy and an NRMSE comparable to RT. However, for the system in the United States, VF simulations result in significant deviations, with NRMSE values reaching up to 50%. Despite these discrepancies, when considering the cumulative yield reflected by the RE, the VF methods appear to balance out their errors on average, resulting in an RE that is closer to the real results compared to RT.

The pure VF and the hybrid (VF + RT) methods produce very similar outcomes. The hybrid method shows a slight improvement over the pure VF method, primarily in RE. However, this improvement is modest, indicating that the hybrid approach does not significantly outperform the pure VF method in most scenarios.

Figure 4 illustrates the monthly variation of rear-side irradiance for VF and RT using different albedo models for the system in the United States. Generally, there is a noticeable overestimation of rear-side irradiance by the VF model across all albedo variations. Another notable feature is the increased yield from February to April, attributed to higher albedo during snowy days in these months. This seasonal variation is not captured by a fixed albedo. However, with the variable albedo model, which accounts for snow cover on the ground, these seasonal patterns are accurately represented, showing a very similar trend to the measured data.

Figure 5 illustrates the bifacial power output per square meter per hour for the Florianópolis location in Brazil. The 4-day example, comprising hourly data points, demonstrates the overestimation of the VF model and the proximity of the RT model to the measured field test data.

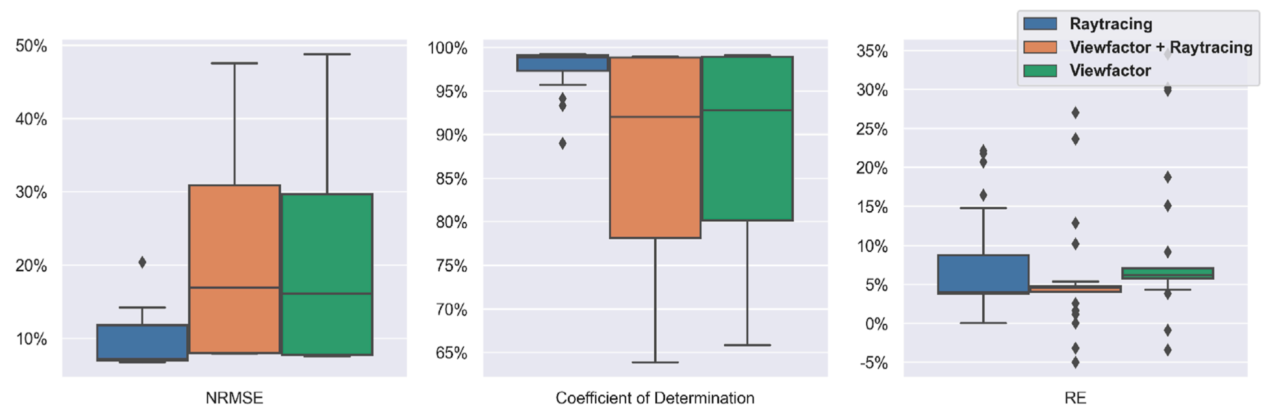


FIGURE 3
NRMSE and coefficient of determination for the single-axis-tracking systems in Golden, United States and Florianopolis, Brazil.

TABLE 3 Simulation results - bifacial energy yield - Golden 2021.

| Irradiance simulation | $R^2$ | RE | NRMSE |
|---|---|---|---|
| Raytracing | 96% | 12.9% | 14.3% |
| Viewfactor | 84% | 9.7% | 33.7% |
| Viewfactor + Raytracing | 84% | 5.9% | 32.4% |

TABLE 4 Simulation results - bifacial energy yield - Florianópolis 2022.

| Irradiance simulation | $R^2$ | RE | NRMSE |
|---|---|---|---|
| Raytracing | 99% | 3.8% | 6.9% |
| Viewfactor | 99% | 6.2% | 7.7% |
| Viewfactor + Raytracing | 99% | 4.1% | 7.9% |

## 4.2 Model selection

The validation results highlight the necessity of using RT for precise hourly performance simulations, while also considering the averaging effects in cumulative yield calculations where VF methods may still provide reasonably accurate estimates. This dual approach ensures a balanced understanding of both detailed performance metrics and long-term energy yield predictions. In cases where a fast estimation of energy yield is sufficient, a combination of simulation models with a relatively short run-time but a reasonable simulation time should be used. The authors propose the simulation path outlined in red on Figure 6, which they consider the optimal approach for that scenario. In the absence of a local weather file, a TMY can be generated. For the module irradiance, the VF model should be used in conjunction with the hourly variable albedo model, in the absence of on-site albedo measurements. Soiling should be calculated according to the location. For a rapid estimation of the energy yield, the adapted one-diode model can be utilised. In general, local measurement data represents the most accurate basis for energy yield simulation. However, if such data are unavailable, alternative methods must be used. Figure 6 illustrates a simulation recommendation.

## 5 Discussion

Focusing on fixed-tilt photovoltaic systems at the sites in Germany and Brazil, the RT method exhibits superior accuracy in calculating bifacial performance, with low NRMSE, high $R^2$ values, and a RE approaching zero on average. The unique topography of the Agri-PV System in Germany, characterized by terraced elevations, poses challenges for accurate modeling, introducing systematic errors due to physical modeling limitations, which were partly compensated by adding an additional inclination to the solar field. In single-axis tracking simulations, RT again yields more precise results in terms of hourly irradiance profiles, as demonstrated by lower NRMSE and higher $R^2$ values. Furthermore, in addition to the RT or VF model, future models could be enhanced by the incorporation of empirical irradiance models (Betcke et al., 2010) or models that utilise linear interpolation (Tsutsui et al., 2006). The seasonal trends captured by the variable albedo model highlight the importance of incorporating dynamic albedo changes in simulations to improve accuracy. That is especially critical in regions with significant seasonal variations, such as snow cover, which can substantially impact the reflective properties of the ground and, consequently, the rear-side irradiance of bifacial PV systems.

In a previous study (Grommes, 2024), the bifacial energy yield of BifacialSimu and the commercial software PVSyst was compared. At the Heggelbach site, a relative error of −13.7% was observed in the PVSyst simulations, with a coefficient of determination of 0.73, indicating a lower level of precision compared to BifacialSimu. At the Golden site in the United States, PVSyst demonstrated a relative error of 13.2% and a coefficient of determination of 0.90, which is more accurate than the VF methods but slightly less precise than the RT simulations from BifacialSimu. At the Florianópolis site, PVSyst demonstrated a considerable cumulative relative error of −11.6%, indicative of a notable underestimation of the bifacial

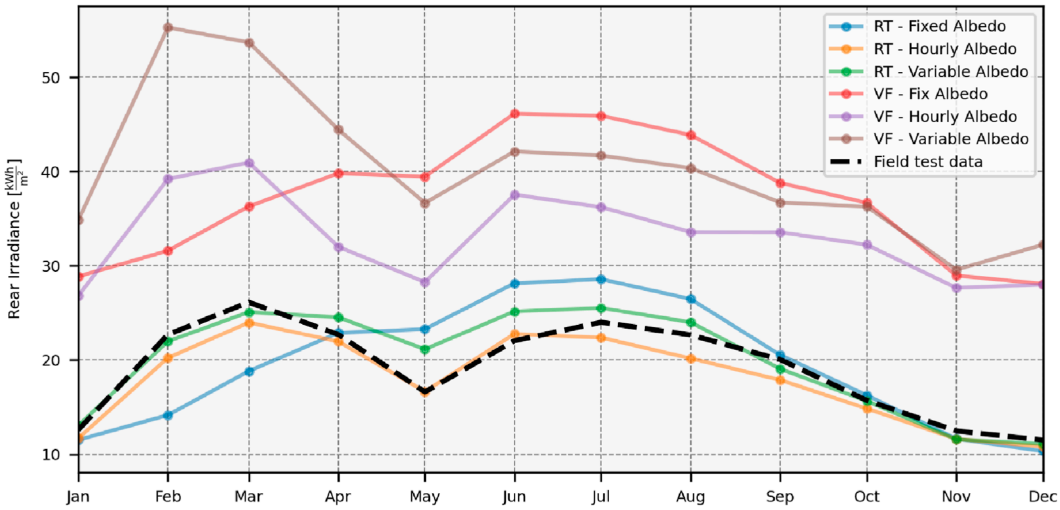


FIGURE 4
Rear side irradiance for different albedo and irradiance models for the single axis tracking system in Golden, United States.

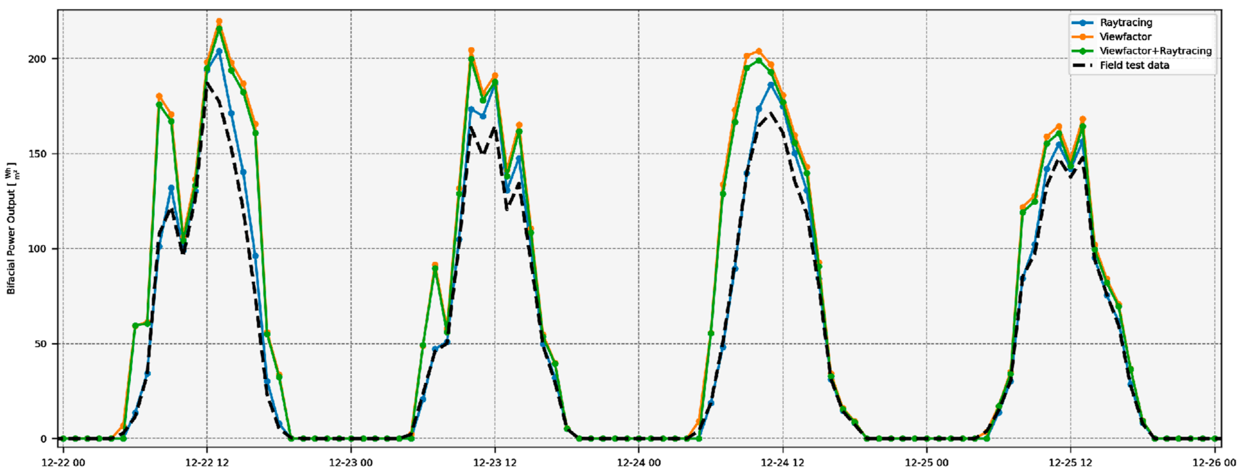


FIGURE 5
Hourly bifacial power output for Florianópolis, Brazil.

yields. However, it also exhibited a remarkably high coefficient of determination of 0.99, suggesting a strong correlation with the actual measured data.

Supplementary Figure A1 in the Appendix presents the absolute error of simulated bifacial performance across the entire simulation period, shown in hourly resolution for all tested models in the fixed tilt configuration in Brazil. Notably, RT simulations exhibit a lower and more consistent error margin. In contrast, the pure VF simulation shows increased errors during the morning and evening hours, when the geometric calculation of irradiance is more complex compared to midday conditions with a high solar altitude. The hybrid simulation mode demonstrates trends similar to the pure VF approach and is marginally improved overall due to the more accurate backside computation. However, the improvement remains limited, as the front-side irradiance calculated via the VF method is significantly higher than the backside irradiance determined by RT.

Summarising the results, RT demonstrated superior accuracy in reproducing hourly irradiance profiles at all locations examined, in contrast to the VF method, which consistently produced higher levels of irradiance on both bifacial surfaces. A challenge in comparing this result to previous estimation is that such analysis are infrequent. Nevertheless, several trends can be confirmed, such as the overestimation of VF on sunny days (refer to table 3 in Liang et al. (2019)). A significant discrepancy between RT and VF techniques was observed at the Florianópolis facility in Brazil. This discrepancy could be attributed to the precision of meteorological data used in each method. Notably, RT utilises DNI, while VF relies on GHI. At the Heggelbach installation in Germany, there was an unexpected underestimation in the simulation results, which deviated from the forecasted slight overestimation. That was due to the omission of certain loss variables in the *BifacialSimu* algorithm. The constant albedo assumption cannot readily explain this phenomenon since

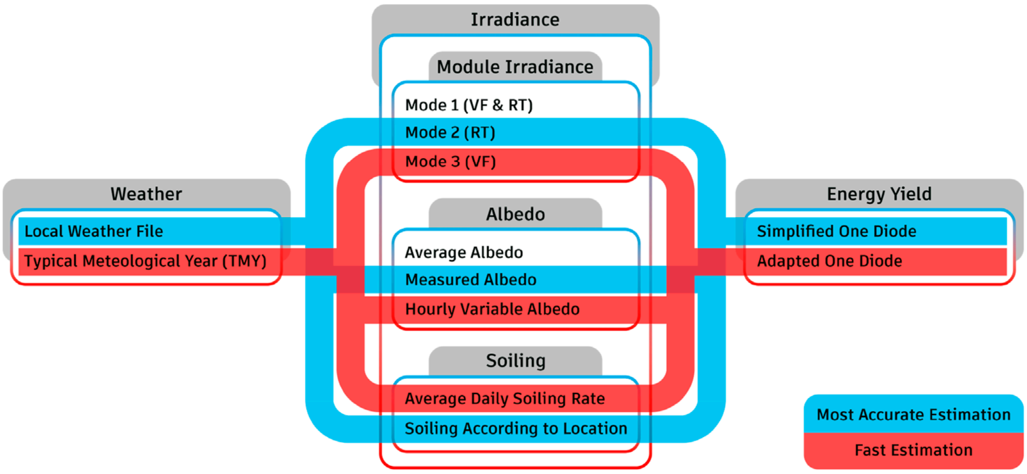


FIGURE 6
Model simulation recommendation for bifacial photovoltaic systems.

the simulated rear-side irradiance surpassed the empirical data. Potential contributing factors to this anomaly may include the physical terracing of the site, which is not accounted for in the simulation framework, or potential inaccuracies in the measurement protocols. The lack of a consistent pattern in the under- or overestimation of irradiance on bifacial surfaces across different locations further complicates the analysis. That implies that the accuracy of simulation methods may vary depending on various factors, such as geographical positioning, altitude differences, and data quality of the measurement and meteorological datasets.

To the best of the authors' knowledge, there are no published studies that assess the accuracy of the cumulative sky model for photovoltaic applications. A study on the NRMSE of the solar contribution, comparing hourly simulations and the cumulative sky function, found a deviation of up to 2.2% ? This indicates that the RT cumulative sky function can serve as a reliable means of approximating the bifacial energy output over a given duration, particularly in instances where intricate hourly projections are deemed unnecessary.

## 6 Conclusion

In conclusion, the article presents a comprehensive validation of *BifacialSimu*, an open-source simulation platform specifically tailored to optimize the performance prediction and enhance the efficiency of bifacial PV systems under a wide range of environmental conditions. By integrating diverse datasets from multiple locations in the United States, Brazil, and Germany, the study demonstrates the superior accuracy of RT methods in comparison to VF methods. While VF provides a quicker simulation process, its tendency to overestimate energy yield limits its reliability, particularly across dynamic environmental scenarios. The validation findings emphasize that RT methods excel in capturing the nuanced hourly irradiance patterns, delivering exceptional precision and aligning more closely with empirical observations.

Moreover, the research highlights the pivotal of variable albedo models in surpassing the limitations posed by fixed albedo values. These models significantly enrich the simulation's fidelity by accounting for temporal fluctuations, such as snow cover, thereby enhancing the bifacial energy yield predictions. Such considerations of variable albedo are crucial in environments where ground reflectivity changes seasonally, impacting the PV system's overall performance. This advancement signals a methodological leap forward in accurately modeling the interaction between ambient conditions and bifacial modules.

The study further advocates for informed model selection based on specific operational conditions, ensuring a well-balanced approach between computational efficiency and simulation precision. For instance, in regions like Florianópolis, Brazil, the RT method achieved an impressive $R^2$ of 99% with an NRMSE of 7.8% for fixed-tilt systems, reflecting a remarkable agreement with measured data. Similarly, in Golden, United States, the RT approach sustained its reliability with an $R^2$ of 96% and an NRMSE of 14.3% for single-axis tracking systems. These results reiterate the necessity of utilizing RT for high-fidelity simulations, particularly when assessing systems under varying environmental influences.

In contrast, the VF methods exhibited notable discrepancies, such as an NRMSE of up to 33.7% in the United States, underscoring their limitations in accurately capturing system performance. Although the hybrid VF and RT approach provided marginal improvements in certain metrics, such as RE, it did not achieve the same degree of precision as RT alone. These insights reinforce the recommendation for using RT in conditions demanding high precision, while acknowledging the potential contributions of VF in less dynamic environments where computational resources may be constrained.

Looking to future enhancements, the open-source platform *BifacialSimu* stands to benefit significantly from additional developments. Enhancing input data flexibility and supporting a broader range of temporal resolutions would enable the simulations to better match the specificities of available datasets and research goals. Furthermore, the integration of cost analysis functionalities could provide valuable user-centric insights into the economic feasibility of bifacial PV projects, thereby expanding the tool's practicality in real-world applications. An expanded albedo database, incorporating models that predict short-term variations based on specific climates or dominant surface types, would further improve simulation accuracy. Additionally, optimizing the computational efficiency of the software, especially within the RT process, could substantially decrease the time required for simulations, making *BifacialSimu* more accessible for extensive studies.

Overall, these enhancements not only promise to bolster the utility of *BifacialSimu* but also contribute substantively to the broader discourse on optimal strategies for modeling bifacial PV systems with various simulation tools. By refining both the technical and practical aspects of the platform, users can achieve more accurate and efficient simulations that meet the diverse demands of modern PV system deployment and research.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## Author contributions

E-MG: Conceptualization, Methodology, Software, Validation, Writing–original draft, Writing–review and editing. MK: Conceptualization, Methodology, Software, Validation, Writing–original draft, Writing–review and editing. J-RH-M: Supervision, Writing–review and editing. HV: Supervision, Writing–review and editing. UB: Conceptualization, Data curation, Supervision, Writing–review and editing.

## Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.



## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2025.1527681/full#supplementary-material

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