

bifacial_radiance: a python package for modeling bifacial solar photovoltaic systems

Silvana Ayala Pelaez¹ and Chris Deline¹

¹ National Renewable Energy Laboratory (NREL)

DOI: [10.21105/joss.01865](https://doi.org/10.21105/joss.01865)

Software

- [Review](#) ↗
- [Repository](#) ↗
- [Archive](#) ↗

Editor: [Melissa Weber Mendonça](#) ↗

Reviewers:

- [@wholmgren](#)
- [@dalonsoa](#)
- [@usethedata](#)

Submitted: 19 October 2019

Published: 08 June 2020

License

Authors of papers retain copyright and release the work under a Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

Summary

bifacial_radiance is a national-laboratory-developed, community-supported, open-source toolkit that provides a set of functions and classes for simulating the performance of bifacial photovoltaic (PV) systems. (Bifacial PV modules collect light on the front as well as the rear side.) bifacial_radiance automates calculations of PV system layout and performance to use along with the popular ray-tracing software tool RADIANCE (Ward, 1994). Specific algorithms include design and layout of PV modules, reflective ground surfaces, shading obstructions, and irradiance calculations throughout the system, among others. bifacial_radiance is an important component of a growing ecosystem of open-source tools for solar energy (William F Holmgren et al., 2018).

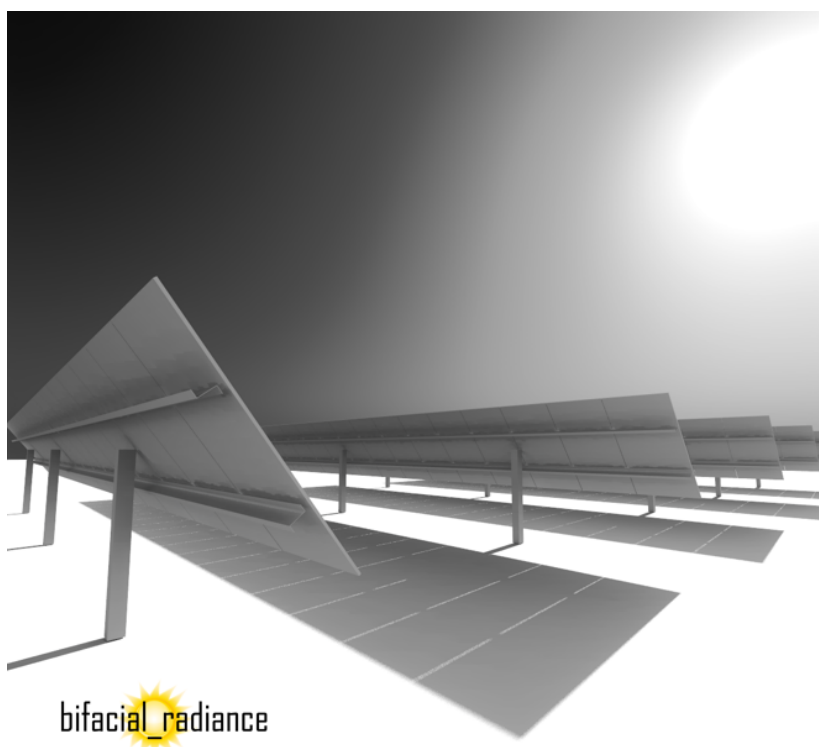


Figure 1: Visualization of a bifacial photovoltaic array generated through bifacial_radiance. Courtesy of J. Alderman.

bifacial_radiance is hosted on Github and PyPi, and it was developed by contributors from national laboratories, academia, and private industry. bifacial_radiance is copyrighted by

the Alliance for Sustainable Energy with a BSD 3-clause license allowing permissive use with attribution. `bifacial_radiance` is extensively tested for functional and algorithm consistency. Continuous integration services check each pull request on Linux and Python versions 2.7 and 3.6. The `bifacial_radiance` application programming interface (API) is thoroughly documented, and detailed tutorials are provided for many features. The documentation includes help for installation and guidelines for contributions. The documentation is hosted at readthedocs.org as of this writing. Github's issue trackers, a Google group and StackOverflow tag provide venues for user discussions and help.

The `bifacial_radiance` API and graphical user interface (GUI) were designed to serve the various needs of the many subfields of bifacial solar panel power research and engineering. The intended audience ranges from PV performance researchers, Engineering Procurement Construction (EPC) companies, installers, investors, consumers and analysts of the PV industry interested in predicting and evaluating bifacial photovoltaic systems. It is implemented in three layers: core RADIANCE-interface functions; Bifacial-Radiance, Meteorological, Scene, and Analysis classes; and the GUI and model-chain classes. The core API consists of a collection of functions that implement commands directly to the RADIANCE software. These commands are typical implementations of algorithms and models described in peer-reviewed publications. The functions provide maximum user flexibility; however, some of the function arguments require an unwieldy number of parameters. The next API level contains the Bifacial-Radiance, Meteorological, Scene, and Analysis classes. These abstractions provide simple methods that wrap the core function API layer and communicate with the RADIANCE software, which provides ray-trace processing capabilities. The method API simplification is achieved by separating the data that represent the object (object attributes) from the data that the object methods operate on (method arguments). For example, a Bifacial-Radiance object is represented by a module object, meteorological data, and scene objects. The `gendaylit` method operates on the meteorological data to calculate solar position with the support of algorithms from `pvlpy` python (William F. Holmgren et al., 2018), and generate corresponding sky files, linking them to the Bifacial-Radiance object. Then the `makeOct` method combines the sky files, module and scene objects when calling the function layer, returning the results from an Analysis object to the user. The final level of API is the `ModelChain` class, designed to simplify and standardize the process of stitching together the many modeling steps necessary to convert a time series of weather data to AC solar power generation, given a PV system and a location. The `ModelChain` also powers the GUI, which provides a cohesive visualization of all the input parameters and options for most common modeling needs.

`bifacial_radiance` was first coded in Python and released as a stable version in Github in 2017 (MacAlpine, Deline, & Marion, 2017), and it was submitted as a U.S. Department of Energy Code project on December of the same year (Deline, Marion, & Ayala Pelaez, 2017). Efforts to make the project more pythonic were undertaken in 2018 (Ayala Pelaez, 2019). Additional features continue to be added as described in Ayala Pelaez, Deline, Marion, et al. (2019), J. S. Stein, Deline, et al. (2019), and in the documentation's "What's New" section.

`bifacial_radiance` has been used in numerous studies, for example, for modeling and validation of rear irradiance for fixed-tilt systems (Ayala Pelaez, Deline, MacAlpine, et al., 2019), estimation of energy gain and performance ratio for single-axis-tracked bifacial systems (Ayala Pelaez et al., 2019a; Berrian, Libal, Klenk, Nussbaumer, & Kopecek, 2019), as well as the study of edge effects (Ayala Pelaez et al., 2019a) and smart tracking algorithms (Ayala Pelaez, Deline, Greenberg, Stein, & Kostuk, 2018); estimation of shading factor from racking structures (Ayala Pelaez, Deline, Stein, et al., 2019), and parameterization of electrical mismatch power losses due to irradiance nonuniformity in bifacial systems (Ayala Pelaez et al., 2019b; Deline, Ayala Pelaez, MacAlpine, & Olalla, 2019, 2020). Sensitivity studies of installation and simulation parameters (Asgharzadeh et al., 2018) and optimization for bifacial fields with the aid of high-performance computing (J. S. Stein, Deline, et al., 2019; J. S. Stein, Prilliman, et al., 2019) have also been performed with `bifacial_radiance`. Furthermore,

benchmarking with other rear-irradiance calculation software has been performed on several occasions (Ayala Pelaez et al., 2018; Capelle, Araya, Haffner, Sayritupac, & Colin, 2019; DiOrio & Deline, 2018). Rear-irradiance calculation software fall into two categories: view-factor and ray-tracing models. View factor models assume isotropic scattering of reflected rays, allowing for calculation of irradiance by integration (Marion et al., 2017). Due-diligence software such as PVSyst or SAM use the view-factor model (Blair et al., 2018; Wittmer & André, 2018). There are also some open-source view-factor models, such as bifacialvf, and PVFactors (Anoma et al., 2017; NREL, 2019). Ray-tracing models simulate multipath reflection and absorption of individual rays entering a scene. Raytracing software such as bifacial_radiance, which is the only available open-source toolkit, offers the possibility of reproducing complex scenes, including shading or finite-system edge effects. Model agreement for view factor and bifacial_radiance software is better than 2% (absolute) when compared with measured results. (Ayala Pelaez et al., 2018).

Plans for bifacial_radiance development include the implementation of new and existing models, addition of functionality to assist with input/output, and improvements to API consistency.

Acknowledgements

The authors acknowledge and thank the code, documentation, and discussion contributors to the project.

S.A.P. and C.D. acknowledge support from the U.S. Department of Energy's Solar Energy Technologies Office. This work was authored, in part, by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding was provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office Agreement Number 34910.

The National Renewable Energy Laboratory is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

References

- Anoma, M. A., Jacob, D., Bourne, B. C., Scholl, Jonathan A., Riley, D. M., & Hansen, C. W. (2017). View factor model and validation for bifacial PV and diffuse shade on single-axis trackers. In *44th IEEE Photovoltaic Specialists Conference Proceedings, Washington, DC*. doi:[10.1109/PVSC.2017.8366704](https://doi.org/10.1109/PVSC.2017.8366704)
- Asgharzadeh, A., Member, S., Marion, B., Deline, C., Hansen, C., Stein, J. S., & Toor, F. (2018). A sensitivity study of the impact of installation parameters and system configuration on the performance of bifacial PV arrays. *IEEE Journal of Photovoltaics*, 8(3), 798–805. doi:[10.1109/JPHOTOV.2018.2819676](https://doi.org/10.1109/JPHOTOV.2018.2819676)
- Ayala Pelaez, S. (2019). *Bifacial solar panels system design, modeling, and performance* (PhD thesis). University of Arizona. Retrieved from <https://repository.arizona.edu/handle/10150/631283>
- Ayala Pelaez, S., Deline, C., Greenberg, P., Stein, J. S., & Kostuk, R. K. (2018). Single-axis tracked bifacial system results. In *5th Bifi PV Workshop, Denver, Colorado* (pp. 1–23).
- Ayala Pelaez, S., Deline, C., Greenberg, P., Stein, J. S., & Kostuk, R. K. (2019a). Model and validation of single-axis tracking with bifacial PV. *IEEE Journal of Photovoltaics*, 9(3), 715–721. doi:[10.1109/JPHOTOV.2019.2892872](https://doi.org/10.1109/JPHOTOV.2019.2892872)

- Ayala Pelaez, S., Deline, C., MacAlpine, S., Marion, B., Stein, J. S., & Kostuk, R. K. (2019). Comparison of bifacial solar irradiance model predictions with field validation. *IEEE Journal of Photovoltaics*, 9(1), 82–88. doi:[10.1109/JPHOTOV.2018.2877000](https://doi.org/10.1109/JPHOTOV.2018.2877000)
- Ayala Pelaez, S., Deline, C., MacAlpine, S., & Olalla, C. (2019b). Bifacial PV system mismatch loss estimation. In *6th BifiPV Workshop, Amsterdam, NL* (p. 1). Retrieved from <https://www.nrel.gov/docs/fy19osti/74831.pdf>
- Ayala Pelaez, S., Deline, C., Marion, B., Muller, M., Stein, J. S., & Stark, C. (2019). The subtle art of bifacial performance modeling bifacial performance modeling. In *12th PV Performance Modeling and Monitoring Workshop, Albuquerque NM*.
- Ayala Pelaez, S., Deline, C., Stein, J. S., Marion, B., Anderson, K., & Muller, M. (2019). Effect of torque-tube parameters on rear-irradiance and rear-shading loss for bifacial PV performance on single-axis tracking systems. In *46th IEEE Photovoltaic Specialists Conference Proceedings, Chicago IL*. Retrieved from <https://www.nrel.gov/docs/fy20osti/73203.pdf>
- Berrian, D., Libal, J., Klenk, M., Nussbaumer, H., & Kopecek, R. (2019). Performance of bifacial PV arrays with fixed tilt and horizontal single-axis tracking: Comparison of simulated and measured data. *IEEE Journal of Photovoltaics*, 9, 1583–1589. doi:[10.1109/JPHOTOV.2019.2924394](https://doi.org/10.1109/JPHOTOV.2019.2924394)
- Blair, N., DiOrio, N., Freeman, J., Gilman, P., Janzou, S., Neises, T., & Wagner, M. (2018). System Advisor Model (SAM) general description (version 2017.9.5). In (pp. 1–19). National Renewable Energy Laboratory, Golden, CO; NREL/TP-6A20-70414. doi:[10.2172/1440404](https://doi.org/10.2172/1440404)
- Capelle, T., Araya, F., Haffner, F., Sayritupac, J., & Colin, H. (2019). A comparison of bifacial PV system modelling tools. In *6th BifiPV Workshop, Amsterdam, NL* (pp. 1–21).
- Deline, C., Ayala Pelaez, S., MacAlpine, S., & Olalla, C. (2019). Bifacial PV system mismatch loss estimation and parameterization. In *36th EU PVSEC, Marseille, France* (pp. 1449–1453). doi:[10.4229/EUPVSEC20192019-5DO.3.4](https://doi.org/10.4229/EUPVSEC20192019-5DO.3.4)
- Deline, C., Ayala Pelaez, S., MacAlpine, S., & Olalla, C. (2020). Estimating and parameterizing mismatch power loss in bifacial photovoltaic systems. *Progress in Photovoltaics: Research and Applications*, 1–13. doi:[10.1002/pip.3259](https://doi.org/10.1002/pip.3259)
- Deline, C., Marion, W., & Ayala Pelaez, S. (2017, December). bifacial_radiance. [Computer software]. doi:[10.11578/dc.20180530.16](https://doi.org/10.11578/dc.20180530.16)
- DiOrio, N., & Deline, C. (2018). Bifacial simulation in SAM. In *5th Bifi PV Workshop, Denver, Colorado*.
- Holmgren, W. F., Hansen, C. W., & Mikofski, M. M. (2018). pvlib python: a python package for modeling solar energy systems. *Journal of Open Source Software*, 3(29), 884. doi:[10.21105/joss.00884](https://doi.org/10.21105/joss.00884)
- Holmgren, W. F., Hansen, C. W., Stein, J. S., & Mikofski, M. A. (2018). Review of open source tools for PV modeling. In *2018 IEEE 45th Photovoltaic Specialists Conference*. doi:[10.5281/zenodo.1401378](https://doi.org/10.5281/zenodo.1401378)
- MacAlpine, S., Deline, C., & Marion, B. (2017). Progress toward efficient bifacial rear irradiance models. In *8th PV Performance Modeling and Monitoring Workshop* (pp. 1–16).
- Marion, B., Macalpine, S., Deline, C., Asgharzadeh, A., Toor, F., Riley, D., Stein, J., et al. (2017). A practical irradiance model for bifacial PV modules. In *44th IEEE Photovoltaic Specialists Conference (PVSC), Washington, DC*. (pp. 1537–1542). IEEE. doi:[10.1109/PVSC.2017.8366263](https://doi.org/10.1109/PVSC.2017.8366263)
- NREL. (2019). bifacialVF. GitHub. Retrieved from <http://github.com/NREL/bifacialvf>

- Stein, J. S., Deline, C., Ayala Pelaez, S., Stark, C., Riley, D., & Carmignani, C. (2019). Bifacial photovoltaic performance optimization using ray tracing and high performance computing. In *Keynote presentation at 2019 Photonics North, Quebec City, Canada*.
- Stein, J. S., Prilliman, M., Stark, C., Nagyvary, J., Ayala Pelaez, S., & Deline, C. (2019). Bifacial performance optimization studies using bifacial_radiance and high performance computing. In *36th EU PVSEC, Marseille, France* (p. 1). ISBN: [3-936338-60-4](#)
- Ward, G. J. (1994). The RADIANCE lighting simulation and rendering system. In *21st Annual Conference on Computer Graphics and Interactive Techniques* (pp. 459–472). doi:[10.1145/192161.192286](#)
- Wittmer, B., & André, M. (2018). Yield simulations for horizontal axis trackers with bifacial pv modules in PVsyst. In *35th EU PVSEC, Brussels, Belgium*. doi:[10.4229/35thEUPVSEC20182018-6CV.2.19](#)