A Review on Bifacial Photovoltaic Systems for Adaptive Inverter Sizing

Radharaman Shaha[1], *Mohammad Israr*[2]
[1,] Post Doctoral (Postdoc) Researcher Lincoln University College, Malaysia
[1]Professor, Department of Electrical Engineering, G H Raisoni Skill Tech University, Nagpur, India
[2]President, Maryam Abacha American University of Nigeria, Kano, Federal Republic of Nigeria
Email: pdf.radharaman@lincoln.edu.my[1] , radharaman2004@gmail.com[1],
president@maaun.edu.ng[2]

Abstract: Bifacial Photovoltaic (BiPV) module is a revolutionary technology in the Photovoltaics as this modules are capable of generating electrical power using both the sides of the module. Using this technology the per unit cost of generation or levelized cost of electricity (LCOE) is decreased and the annual energy production is increased. In order to increase the generation and reduce the cost, the system design particularly at inverter level plays an important role. This review paper analyzes the recent research that has been conducted on the designing of the solar power plants based on the BiPV. Bifacial gain, albedo dependence, and orientation schemes are all factors that might have an impact on the inverter loads in bulk plants employing BiPV panels. The study investigates novel methods that can be utilized to enhance the design of inverters, including Power Sizing Ratio (PSR) tuning, flexible power point tracking, and topology selected. Temperature stress on inverters is developed due to the sizing issues of inverters in a BiPV based solar power plant, which causes them to deteriorate over time. This study concludes with potential future choices for the design of adaptive inverters that are both powerful and cost-effective to integrate with the BiPV.

Keywords: Bifacial Photovoltaic; Maximum Power Point Tracking; Power Sizing Ratio; Levelized cost of energy; Net Present Value

---

Introduction

The BiPV technology has emerged as the undisputed victor when it comes to extracting the maximum amount of energy from a system while simultaneously minimizing the LCOE to the greatest extent possible. BiPV are able to absorb solar light from both the front and the back. In other words, largely depending on the albedo of the site, they have the potential to improve energy production by anywhere from five percent to more than thirty percent. Bifacial technology is expected to hold between 70 and 90 percent of the market from now until the end of the decade, according to blueprints developed by the industry experts [1,2].

In spite of the fact that BiPV has obvious advantages, it makes the process of designing solar power plants' electrical systems more challenging [3]. The PV converter, which is responsible for converting direct current (DC) into alternating current (AC) that is compatible with the grid, is faced with challenges that have never been encountered before in the history of BiPV systems. The inverter is subjected to increased levels of thermal and electrical stress as a result of the rear side producing an increasing amount of variable DC power [4,5]. Over time, this will result in a decrease in its efficiency as well as a decrease in its reliability. As a result of this, straightforward guidelines for selecting the appropriate inverter size are no longer effective in designing of the solar plant employing the BiPV [6].

There is a discernible rising trend between the amount of energy gained and the albedo. This is due to the fact that bifacial modules are extremely sensitive to the reflectance of the ground. There is a direct correlation between higher albedo conditions and an increase in the quantity of electricity generated from the base [7]. Additionally, the PSR–LCOE connection has a non-linear form, which demonstrates that there is a sweet spot for sizes where economic efficiency is at its optimum [8]. Any size that is greater than this results in lesser returns since a greater number of resources are either harvested or not used. Moreover, the thermal profile demonstrates that there is an inverse relationship between the running temperature and the duration of the inverter [9,10]. In bifacial systems that have a high irradiation, this demonstrates how critical it is to minimize extended heat stress to a significant degree. Additionally, the irradiance–power graph remains practically straight, which is a confirmation of what we anticipated photovoltaics to do as the output of the sun gradually increases in process [11]. These tendencies, when viewed as a whole, demonstrate how challenging it is to establish the optimal balance between maximizing the amount of energy that can be extracted from a system and ensuring that it remains stable. This demonstrates how essential it is to make use of integrated analytical modeling in order to achieve the highest possible level of technological efficacy [12,13].

We require comprehensive analytical models that are able to assess the irradiance from the rear side, simulate thermal cycling, and determine the optimal settings for the inverter in order to strike a balance between energy yield and component degradation. In this article, the most recent mathematical modeling techniques that are utilized to determine the optimal inverter design for bifacial solar panels are discussed that are currently available. This brings together the various approaches that are now in use, as well as optimization techniques and the inevitable trade-offs that exist between the cost of the system, the amount of energy it generates, and the degree to which it is reliable [14,15.16,17]

Overview of Bifacial Solar Panel Characteristics

In order to get the most out of photovoltaic inverters, it is necessary to have an understanding of the differences between the electrical and visual aspects of BiPV. There are a number of parameters that collectively influence the success of BiPV systems [17,18].

i. Bifaciality Factor: It is a measurement that indicates how efficient the rear side is in comparison to the front side, when subjected to Standard Test Conditions (STC) [19]. The bifaciality factors of commercial BiPV cells, such as those designed using Passivated Emitter and Rear Cell (PERC) architectures, range from 75 percent to 65 percent [20]. TOPCon, which stands for tunnel oxide passivated contact, and HJT, which stands for Heterojunction Technologies , are two more advanced technologies that are capable of reaching bifaciality factors that are greater than 90% [21].
ii. Albedo and Rear-Side Irradiance: The most important feature that influences the amount of energy collected from the rear side is albedo [22,23]. It is the ratio of the irradiance that is reflected from the ground to the irradiance that is reflected from the earth's surface [25]. The albedo of a surface can range anywhere from ten percent to ninety percent, depending on the characteristics of the surface, such as grass, gravel, fresh snow, or reflecting polymeric membranes [26.27]. There is a correlation between highly reflecting surfaces and peak solar altitudes, which results in significant power spikes.To deal for these occurrences, inverters need to be constructed. [28, 29,30].

iii. Module Height and Row Spacing: The overall design of the photovoltaic array has a significant impact on the amount of light that is diffused and reflected from the rear of the array. It is possible to lower the amount of ground self-shading by increasing the module mounting height to, for example, two meters and adjusting the inter-row spacing by adjusting the pitch. Because of this, the total DC current that is being fed into the inverter is increased [31] for the process.

In terms of tracking and direction, the majority of systems have a fixed tilt and face south. However, East-West BiPV designs that are positioned vertically produce two power peaks, one in the morning and one in the afternoon scenarios. This results in a larger daily generating window, which in turn alters the load profile of the inverter and reduces the amount of clipping that occurs at midday. It is also possible to boost both rear and front irradiance by combining BiPV modules with single-axis tracking (SAT) systems. This combination results in the LCOE throughout the majority of the world's land regions [10,11,24,31] for the process.

Comparative Summary of Key Findings

It is the ability of bifacial solar panels to gather energy from both sides that is the primary advantage of these panels. The ratio of rear-to-front nominal efficiency is the bifaciality factor, which is used to assess this. The bifaciality factor typically falls somewhere between 0.60 and 0.95, depending on the structural configuration of the cell. The applications in the real world reveal significant energy gains. Compared to monofacial plants, for instance, large bifacial plants in the United Kingdom have an energy yield advantage that ranges from 15.12% to 17.31% overall. Additionally, vertically mounted bifacial photovoltaic (PV) systems with high-junction thermoelectric (HJT) cells have the potential to generate up to 26.91% more power than slanted monofacial systems during specific times of the day. This provides these systems with distinctive generation profiles that are tailored to meet the requirements of the peak grid [18, 24].

When it comes to the operation of an inverter, bifacial panels also are distinguished by their distinct thermal and optical features. When looking at other wavelengths, they are better at absorbing infrared light, which can boost energy yields in certain settings thanks to their ability to absorb infrared lights. This is because bifacial modules do not have a fully metalized back contact, which allows them to function at temperatures that are lower than those of monofacial modules. This is due to the fact that they do not absorb as much infrared radiation, which therefore results in a lower rate of heat loss. One of the most significant aspects that has an impact on the design of inverters is the fact that the radiation from the rear is not dispersed evenly throughout space. A number of factors, including edge effects, inter-row spacing, and structural components, are responsible for the uneven distribution of light across the rear of the module. Because of this, there is a mismatch in the current between cells that are connected in series. This mismatch, if it is not taken into consideration, will result in a significant reduction in the amount of useful power that is transmitted to the inverter. As a result, it is necessary to have sophisticated models and distinct inverter topologies [19–21, 22–30] for the process.

Table 1. key studies that integrate analytical modeling with BiPV inverter optimization

Study	Focus Area	Analytical Method / Model	Key Findings & Inverter Implications

[10]	Orientation & Load Matching	System Advisory Model (SAM)	Vertical East-West bPV configurations generate dual peaks, extending generation hours. Lowers inverter sizing requirements by flattening the peak load profile.
[11]	Global LCOE & Tracking	Spatial modeling, Monte Carlo sensitivity analysis	Bifacial-1T systems achieve the lowest LCOE globally. Inverter capacity must be increased by 20% to accommodate bifacial gain.
[12]	Power Sizing Ratio (PSR) Optimization	MATLAB simulation, Pattern Search Algorithm (PSA)	Identified an optimal PSR of 1.19. Highlighted the trade-off between maximizing energy capture and minimizing inverter clipping costs.
[13]	PV Array & Inverter Sizing	Multi Verse Optimization (MVO), Isotropic sky models	Determined optimum sizing ratios (Rs) of 0.87 to 0.92 for multi-megawatt bPV plants to minimize LCOE and contain power losses.
[14]	Inverter Reliability & Thermal Stress	Foster electro-thermal model, Rainflow counting, Monte Carlo	Bifacial panels increase thermal stress on IGBTs. High bifacial gain (>30%) severely reduces inverter B10 lifetime (e.g., from 34 years to 1.5 years at the component level).
[17]	Yield Gain Quantification	Osterwald model, NRMSE optimization	Numerically estimated bifaciality factors at the stringbox level, revealing 3% to 5.3% real-world yield gains depending on site albedo.
[21,23]	Topology & Mismatch	MCRT optical + PV Mismatch electrical models	Rear Irradiance non-uniformity causes mismatch. MLPE/individual optimization yields 1.4% more energy than string inverters.
[25]	Grid Stability (LVRT)	Review of GFM inverter control architectures	Advanced current-limiting (Current Saturation, Virtual Impedance) is mandatory for GFM inverters to survive grid faults and maintain synchronization.
[26]	System Sizing & Clipping	Experimental data & SAM financial modeling	DC/AC oversizing (1.3 to 1.5) causes clipping losses, but high-albedo setups still maximize NPV and reduce LCOE by up to 4%.
[28]	Intelligent	Hybrid AI Algorithm	AI-driven scheduling handles

	Scheduling	(COA-BKA)	high-altitude irradiance volatility, achieving 98% accuracy in 4.5s, optimizing inverter dispatch to loads.
[29]	Real-Time Control	Empirical nonlinear regression models	"Equivalent irradiance" models accurately predict V_{mp} and I_{mp}, enabling faster, model-based MPPT algorithms in inverters.
[31]	Tracking vs. Fixed	SAM modeling across six global desert climates	1-axis tracking combined with bifacial panels offers the most economically viable LCOE (as low as 2.45 ¢/kWh) compared to fixed or 2-axis.

Key Contribution

Even though modeling has improved, it is still hard to find the best inverter for a BiPV system.

Lack of Standardization: Manufacturer datasheets are not reliable because there isn't a single meaning of bifacial gain and bifaciality factors that work in all field conditions. While standards like IEC 60904-1-2 are being made, it is hard to get the right size transformer for a building before it is built because there aren't any clear input factors. [7,19,32] Shadows are cast on the backside by torque tubes, tracking structures, and changing ground plants, which leads to mismatches and complex shade. It's necessary to use GPU-based 3D modeling to accurately find electrical difference and create multi-MPPT inverter designs, since 2D View Factor models often miss these edge effects. [21,22]

Taking care of thermal and extreme weather: Reliability models say that the loss of heat from the BiPV system transformer is a big problem, especially in dry, high-Irradiance areas. It is important to look into more advanced active cooling methods for transformers and long-lasting materials for power semiconductors. Tracking methods need to meet certain standards so that buildings are safe from bad weather without causing huge drops in generator power. [4, 7, 14] Different types of bPV systems, like vertical agrivoltaics, floating solar, and noise-barrier PVs, produce very uneven daily power trends. A big area of study will be optimizing inverter behavior, which includes using smart Volt Var settings to control the amount of hosting capacity on the distribution grid without having to buy expensive battery storage [15, 20, 24].

Conclusions

Bifacial photovoltaic panels alter the process of solar energy generation by lowering the LCOE and increasing yields. The operation of PV inverters is significantly altered as a result of this modification. In order to improve the design of a BiPV inverter, it was discovered that it is necessary to make use of sophisticated mathematical models rather than using static, one-sided assumptions. Changing rear-side irradiance can be predicted by view factor and ray-tracing models, while thermal stress and needless clipping losses can be kept to a minimum using electrical and electro-thermal models. Studies have shown that determining the optimal PSR, selecting the appropriate tracking systems, and ensuring that the capacity of the inverter corresponds to the load patterns are all sensitive balances. The BiPV technology maximizes the amount of energy that is absorbed, but it also places a great deal of stress on the components of the generator, which makes them less dependable. It is only via the development of superior analytical models that next-generation BiPV power plants will be able to function properly. This will allow for the manufacture of transformers that are more cost-effective, compatible with the grid, and robust enough to meet the additional energy requirements of bifacial processes.

It is essential to make use of mathematical models in conjunction with one another in order to get the most out of bifacial solar systems. Standard inverter sizes and controls are not compatible with bifacial modules because they make use of a dynamic and non-uniform rear-side light. It is possible for system designers to make precise predictions regarding DC yields with the use of modern optical ray tracking, electrical mismatch models, and real-time digital twins software. With the help of this predictive power, the DC/AC ratio of the inverter is adjusted in such a way that inverter clipping losses are reduced to a minimum while both NPV and LCOE are optimized. In addition to this, these models choose the optimal topology, provide an explanation as to why module-level power electronics are required to reduce mismatch, and define robust grid-forming inverter control approaches that maintain grid stability.

References

1. VDMA-Verband Deutscher Maschinen- und Anlagenbau e.V, International Technology Roadmap for Photovoltaic (ITRPV) - 2023 results, Frankfurt am Main, 2024. https://www.vdma.org/international-technology-roadmapphotovoltaic
2. BloombergNEF, 3Q 2024 Global PV Market Outlook, (2024). https://about.bnef. com/blog/3q-2024-global-pv-market-outlook/ (accessed November 6, 2024).
3. Al Garni, H. Z, "A performance modeling and optimal orientation of bifacial PV modules: A case study from Saudi Arabia", Results in Engineering, 29, 109175. https://doi.org/10.1016/j.rineng.2026.109175
4. Ramavath, M., & Venkata, R. K. P, "Comparative reliability and performance analysis of PV inverters with bifacial and monofacial panels", International Journal of Power Electronics and Drive System (IJPEDS), 16(3), 1970-1982. https://doi.org/10.11591/ijpeds.v16.i3.pp1970-1982
5. Abdullah Al Mehadi et.al, "Design, Simulation and Feasibility Analysis of Bifacial Solar PV System in Marine Drive Road, Cox's Bazar", 2021 International Conference on Science & Contemporary Technologies (ICSCT), 5-7 Aug. 2021. https://doi: 10.1109/ICSCT53883.2021
6. Guari Borrull, M. (2019) "Performance Optimization of Bifacial Module PV Power Plants Based on Simulations and Measurements" (Doctoral dissertation).
7. IEA PVPS Task 13. (2024). "Best Practices for the Optimization of Bifacial Photovoltaic Tracking Systems". International Energy Agency Photovoltaic Power Systems Programme.
8. Hassen ayed chraiga, Othman Jeddi, Zaher Khantouch. "MATLAB based modeling to study the performance of bifacial solar PV system under various operating conditions". International Conference on Mechanics and Energy, association international en mécanique et Energie, Dec 2023, sousse, Tunisia. ⟨hal-04709785⟩.
9. Nasiri, R., Khayamy, M., Rashidi, M., Nasiri, A., & Bhavaraju, V. (2018) "Optimal Solar PV Sizing for Inverters Based on Specific Local Climate", 2018 IEEE, 6214-6219. DOI:10.1109/ECCE.2018.8557994

10. Muhammad Zubair, Ghulam Abbas, “Optimization of bifacial PV panels in a residential sector for maximum economic benefits based on load profile”, Energy Reports, Volume 13,2025,Pages 5252-5265, ISSN 2352-4847.
https://doi.org/10.1016/j.egyr.2025.04.062.
11. Carlos D. Rodríguez-Gallegos, Haohui Liu, Oktoviano Gandhi, Jai Prakash Singh, Vijay Krishnamurthy, Abhishek Kumar, Joshua S. Stein, Shitao Wang, Li Li, Thomas Reindl, Ian Marius Peters, “Global Techno-Economic Performance of Bifacial and Tracking Photovoltaic Systems, Joule”, Volume 4, Issue 7, 2020, Pages 1514-1541, ISSN 2542-4351.
https://doi.org/10.1016/j.joule.2020.05.005.
12. Hazim Imad Hazim et al. “Techno-economic optimization of photovoltaic (PV)-inverter power sizing ratio for grid-connected PV systems”, Results in Engineering, Volume 23, 2024,102580,ISSN 2590-1230.
https://doi.org/10.1016/j.rineng.2024.102580.
13. T E K Zidane et al. “PV array and inverter optimum sizing for grid-connected photovoltaic power plants using optimization design”, 2021 J. Phys.: Conf. Ser. 1878 012015.
https://doi.org/10.1088/1742-6596/1878/1/012015.
14. Kshatri, S. S., Dhillon, J., Mishra, S., Tariq, R., Sharma, N. K., Bajaj, M., Rehman, A. U., Shafiq, M., & Choi, J.-G. (2022). “Reliability Analysis of Bifacial PV Panel-Based Inverters Considering the Effect of Geographical Location”. Energies, 15(1), 170.
https://doi.org/10.3390/en15010170.
15. Lee, S., Kim, G., Son, S., & Lee, J. (2025) “Comparative Analysis of the Substitution Effect of Smart Inverter-Based Energy Storage Systems on the Improvement of Distribution System Hosting Capacity Using Vertical Photovoltaic Systems”. Energies, 18(16), 4307. https://doi.org/10.3390/en18164307.
16. Braga, D. S., et al. (2023), “Performance of bifacial PV modules under different operating conditions in the state of minas gerais in Brazil”, Renew. Energy Environ. Sustain. 8, 23 (2023).
https://doi.org/10.1051/rees/2023021.
17. Malgaroli, G., Matturro, F., Cagnetti, A., Vivino, A., Terzi, L., Ciocia, A., & Spertino, F. (2025). “Quantification of Yield Gain from Bifacial PV Modules in Multi-Megawatt Plants with Sun-Tracking Systems”. Solar, 5(4), 49.
https://doi.org/10.3390/solar5040049.
18. Badran, G., & Dhimish, M. (2024), “A comparative study of bifacial versus monofacial PV systems at the UK’s largest solar plant”, Clean Energy, Volume 8, Issue 4, August 2024, Pages 248–260. https://doi.org/10.1093/ce/zkae043.
19. Raina, G., & Sinha, S. (2022), “A holistic review approach of design considerations, modelling, challenges and future applications for bifacial photovoltaics”, Energy Conversion and Management, Volume 271, 1 November 2022, 116290. https://doi.org/10.1016/j.enconman.2022.116290
20. Garrod, A., Ghosh, A, “A review of bifacial solar photovoltaic applications”, *Front. Energy* **17**, 704–726 (2023).
https://doi.org/10.1007/s11708-023-0903-7
21. Ernst M, Conechado GEJ, Asselineau CA, “Accelerating the simulation of annual bifacial illumination of real photovoltaic systems with ray tracing”, iScience. 2021 Dec 25;25(1):103698.
https://doi.org./10.1016/j.isci.2021.103698

22. Ernst, M., Liu, X., Asselineau, C.-A., Chen, D., Huang, C., & Lennon, A. (2024), "Accurate modelling of the bifacial gain potential of rooftop solar photovoltaic systems", Energy Conversion and Management, Volume 300, 15 January 2024, 117947. https://doi.org/10.1016/j.enconman.2023.117947
23. Halwani, S., Hamid, A.-K., Ahmad, F. F., & Hussein, M. (2025), "Comparative analysis of experimental and modelling of bifacial PV panel: a step towards digital twin", International Journal of Thermofluids, Volume 29, September 2025, 101377. https://doi.org/10.1016/j.ijft.2025.101377
24. Badran, G., Dhimish, M, "Comprehensive study on the efficiency of vertical bifacial photovoltaic systems: a UK case study", Sci Rep 14, 18380 (2024). https://doi.org/10.1038/s41598-024-68018-1
25. Ordono, Ander & Sanchez-Ruiz, Alain & Zubiaga, Markel & Asensio, Francisco Javier & Cortajarena, Jose Antonio, 2024. "Current limiting strategies for grid forming inverters under low voltage ride through," Renewable and Sustainable Energy Reviews, Elsevier, vol. 202(C). https://doi.org/10.1016/j.rser.2024.114657
26. Kaewnukultorn, T., Sepúlveda-Mora, S. B., Purnell, R., & Hegedus, S, "Electrical and Financial Impacts of Inverter Clipping on Oversized Bifacial Photovoltaic Systems", Energies 2024, *17*(22), 5658. https://doi.org/10.3390/en17225658.
27. Desai, A., Mukhopadhyay, I., & Ray, A. (2022). Feasibility Assessment of Bifacial Rooftop Photovoltaic Systems in the State of Gujarat in India. Frontiers in Energy Research, 28 June 2022 Sec. Sustainable Energy Systems, Volume 10 – 2022. https://doi.org/10.3389/fenrg.2022.869890
28. Hu, H., Xiong, X., Wang, S., Yan, T., Zhang, Y., & Gan, S, "Framework design and empirical analysis of intelligent scheduling system for high-altitude photovoltaic power generation based on mixed optimization of long-nosed raccoon optimization algorithm and black winged kite optimization algorithm (COA-BKA)", Discover Computing 28, 47 (2025). https://doi.org/10.1007/s10791-025-09558-6
29. Mannino, G., Tina, G. M., Jiménez-Castillo, G., Cacciato, M., Bizzarri, F., & Canino, A, "Nonlinear and multivariate regression models of current and voltage at maximum power point of bifacial photovoltaic strings", Solar Energy, Volume 269, 2024, 112357, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2024.112357
30. Ayadi, O., Rinchi, B., Al-Dahidi, S., Abdalla, M. E. B., & Al-Mahmodi, M, "Techno-Economic Assessment of Bifacial Photovoltaic Systems under Desert Climatic Conditions", Sustainability, *16*(16), 6982. https://doi.org/10.3390/su16166982
31. Yakubu, R. O., Mensah, L. D., Quansah, D. A., & Adaramola, M. S. (2024), "A systematic literature review of the bifacial photovoltaic module and its applications", *J. Eng.*2024, e12421 (2024). https://doi.org/10.1049/tje2.12421