This article has been accepted for publication in IEEE Journal of Photovoltaics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JPHOTOV.2024.3414131

Short Term Performance and Degradation Trends in Bifacial vs Monofacial PV Systems: A UK Case Study

Ghadeer Badran, *Student Member, IEEE*, and Mahmoud Dhimish, *Member, IEEE*

***Abstract*—This study presents an empirical analysis of the degradation rates in eight bifacial photovoltaic (PV) systems over the initial two years of operation, comparing glass/transparent-backsheet (G/tB) and glass/glass (G/G) configurations against traditional monofacial systems. Utilizing data from various UK locations, we assessed systems using RdTools for degradation rate estimation—a methodology that ensures accuracy by adjusting for environmental factors such as soiling and irradiance variations. Our findings indicate that the sampled G/tB bifacial systems exhibit higher annual degradation rates (-1.46% to -2.30%), significantly exceeding the solar industry's average (-0.8%), while the G/G configurations in our study show comparatively lower rates (-0.90% to -1.17%). Monofacial systems maintained degradation rates closer to the industry benchmark (-0.62% to -0.94%), suggesting more stable long-term performance. This paper contributes novel insights into the comparative durability and efficiency of bifacial versus monofacial PV technologies based on a specific set of systems and emphasizes the critical need for advancements in bifacial system design and material quality to improve their long-term reliability.**

***Index Terms*—Photovoltaics, Solar Energy, Bifacial, Reliability Analysis, Degradation Estimation.**

I. INTRODUCTION

SOLAR photovoltaic (PV) technology has emerged as a fundamental component of the renewable energy landscape, providing a clean and sustainable response to escalating global energy requirements [1]. At the heart of this technology lies the process of converting sunlight into electricity using semiconducting materials. Historically, the field has been dominated by monofacial PV modules [2], which capture sunlight from only one side. However, the quest for more effective and economical energy solutions has spurred the development of bifacial modules [3,4]. These innovative modules are capable of harnessing sunlight from both sides. While bifacial PV technology may not directly influence efficiency metrics as traditionally measured, it represents a pivotal advancement in improving the overall energy yield and operational economics of solar energy systems.

Bifacial PV modules are designed to capture not just the direct sunlight that falls upon their front surface, but also the sunlight that reaches their rear side through direct and diffuse ground reflections due to the albedo of the ground [5,6]. This innovative design allows for the absorption of light reflected off surrounding surfaces and the diffused components of sunlight, providing >3% increase to energy yield compared to monofacial modules [7]. The ability of bifacial modules to capitalize on diffuse light and ground reflections due to albedo, is particularly beneficial in regions with high ground reflectivity or in installations where the ground cover is engineered to enhance reflectivity [8].

Despite the wealth of data on monofacial systems, the exploration into the degradation rates of bifacial PV systems remains relatively nascent. This is, in part, due to the more recent entry of bifacial technology into the market and the limited scope of long-term operational data. Bifacial modules, although rapidly growing in popularity due to their potential for higher energy yield (e.g., 12% to 21% [9]), present a new technology that complicate degradation analysis. The ability of bifacial panels to absorb light from the rear surface introduces additional factors such as the variability of ground albedo [3,6] and the installation environment, which are not accounted for in traditional monofacial capacity testing models. Consequently, the industry lacks a detailed understanding of how these factors influence the long-term performance and degradation rates of bifacial PV systems.

The discrepancy in the depth of research between monofacial and bifacial PV systems creates a knowledge gap that this paper aims to bridge. While the deployment of bifacial systems is increasing globally, their operational histories are shorter, and the datasets are less extensive compared to monofacial systems. This lack of detailed degradation data has made it challenging to accurately predict the performance and financial viability of bifacial PV projects. By concentrating on empirical data and in-depth analysis, this paper endeavours to shed light on the degradation patterns of bifacial systems, offering a clearer picture of their long-term performance metrics. The subsequent sections will introduce the unique approach of this study, highlighting its contribution to the field and the novel insights it provides into the degradation behaviours of bifacial PV systems.

Manuscript received 14 December 2023; revised 26/03/2024 and 24/05/2024. This work was supported by EPSRC IAA project: Next-Generation Vertically Mounted Bifacial Solar Panels: Conceptualisation, Field Testing, and Energy Performance Monitoring.

Badran G. and Dhimish M. are with the Laboratory of Photovoltaics, School of Physics, Engineering and Technology, University of York, York YO10 5DD, UK. (e-mail: Ghadeer.badran@york.ac.uk; Mahmoud.dhimish@york.ac.uk).

This article has been accepted for publication in IEEE Journal of Photovoltaics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JPHOTOV.2024.3414131

II. Description of Bifacial PV Systems

In this work, we have conducted an empirical analysis of eight bifacial PV systems to assess their performance and degradation during the first two years of operation. Our dataset encompasses a comparative examination of two distinct types of bifacial PV configurations, glass/transparent-backsheet (G/tB), and glass/glass (G/G). Each type includes four systems, making a total of eight individual systems under scrutiny. These systems are strategically installed across various locations within the UK and were commissioned in the latter part of 2021 (2 years of data). The location and capacity of the examined PV systems are shown in Fig. 1.

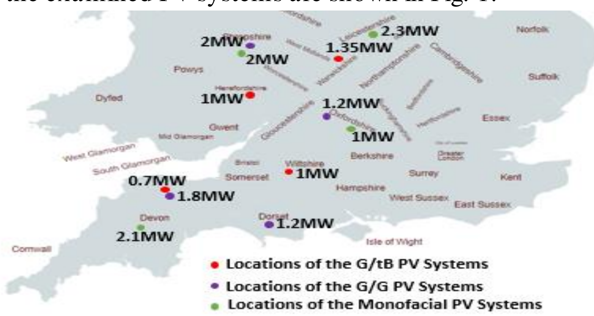

Fig. 1. Locations and capacity of the examined PV systems.

Our research employs datasets derived from systems supplied by four distinct PV manufacturers, each contributing a system characterized by G/tB, G/G, and monofacial configurations. To uphold confidentiality and mitigate any risk of reputational damage, we have chosen not to disclose specific details about the manufacturers. All modules in these sites use Monocrystalline Silicon (Mono-Si) cell technology. Additionally, it is important to note that different manufacturers supplied systems at each location, ensuring a diverse representation of available technologies. For example, the manufacturer for G/tB and G/G are the same, such as manufacturer 1 from G/tB also being manufacturer 1 from G/G, as will be presented in this work.

Additionally, to provide a comprehensive analysis and establish a performance baseline, we have also examined four monofacial PV systems. These systems serve as a control group to draw effective comparisons between monofacial and bifacial PV technologies. Like their bifacial counterparts, the monofacial systems were also commissioned within the same time frame, between November and December of 2021, ensuring a consistent period of operation for direct comparison. Moreover, the systems evaluated are mounted at tilt angles between 34 and 37 degrees and are south-oriented, with azimuth angles ranging from -5 to +7 degrees relative to true south. Additionally, the height of the racking systems varies slightly, ranging from 0.9 to 1.2 meters above ground level across all systems.

II. Degradation Estimation Method

Our study meticulously quantifies the degradation rates of PV systems using RdTools, a leading open-source software designed specifically for PV data analysis [10]. This choice is in direct response to inquiries regarding our computational methodology and to ensure alignment with industry-standard practices. RdTools enables a detailed examination of system performance over time, isolating the genuine degradation signal from operational data by correcting for external factors such as soiling and irradiance variations [11]. This approach ensures that the degradation rates we present are derived from system-level performance metrics, rather than module-level assessments or external estimates. The RdTools employs a robust statistical framework to normalize PV system output, adjusting for environmental conditions like solar irradiance and temperature. Therefore, data were used directly in RdTools without the need for further filtration and processing.

Using RdTools, two key parameters can be extracted, these parameters provide valuable insights into the degradation behavior and expected lifespan of PV systems:

- Shape parameter (β): This parameter indicates nuanced modelling of failure rates, capturing the idiosyncratic trends of PV system degradation. These trends could be escalating due to cumulative wear or declining as a result of the early resolution of defects.
- Scale parameter (η): This parameter denotes the characteristic life, reflecting the time span by which a certain percentage of the PV systems are expected to exhibit degradation.

III. Results

A. G/tB Bifacial PV Systems

The degradation rates of G/tB bifacial PV systems from four manufacturers were analyzed, focusing on the Weibull distribution's scale parameter to quantify system reliability and degradation; Fig. 2 presents a comparative overview. The analysis reveals varied degradation rates, indicating differences in system longevity and performance: Manufacturer 1's system degrades at -1.66%/year, showing consistent performance. Manufacturer 2's system has a higher degradation rate of -2.30%/year, hinting at potential quality inconsistencies. Manufacturer 3's system shows slightly better durability with a -1.46%/year degradation rate. Lastly, Manufacturer 4's system degrades at -1.80%/year, positioning it between Manufacturers 2 and 3 in terms of efficiency loss, with relatively stable performance as suggested by its low shape factor.

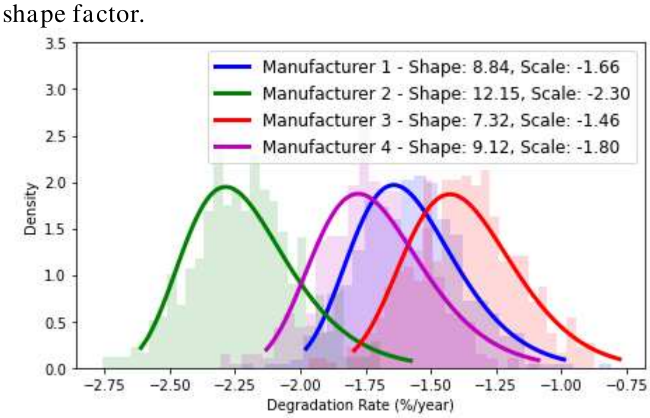

Fig. 2. Results of the G/tB PV systems degradation rate.

This article has been accepted for publication in IEEE Journal of Photovoltaics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JPHOTOV.2024.3414131

This collective degradation profile is notably distant from the industry standard of an average annual degradation rate of around -0.7% [12]. Considering that these degradation rates are the culmination of just two years' worth of operational data, the accelerated decline in system efficiency is particularly troubling. It points to potential underlying issues such as suboptimal manufacturing processes, inferior material quality, or perhaps environmental factors that have not been adequately accounted for in the design and deployment of the G/tB bifacial PV systems.

B. G/G Bifacial PV Systems

In the evaluation of G/G bifacial PV systems from four manufacturers, depicted in Fig. 3, the observed degradation rates demonstrate an interesting trend when compared to the previously analyzed G/tB bifacial PV systems. Manufacturer 1 shows a degradation rate of -0.90%/year, while Manufacturer 2 exhibits a slightly higher rate of -0.96%/year. Manufacturer 3 PV system degrade at a rate of -1.09%/year, and Manufacturer 4 PV system present a rate of -1.17%/year. Although each of these rates is higher than the industry standard of -0.7%/year, they are, on average, more favourable than the degradation rates observed in the G/tB bifacial systems (Fig. 2).

G/G bifacial modules have several advantages over G/tB bifacial modules. The G/G configuration enhances durability and longevity because both sides of the module are protected by glass, making them less susceptible to environmental degradation compared to the backsheet in G/tB modules. This protection significantly improves the modules' resistance to moisture ingress and UV exposure [13], leading to a lower degradation rate over time. Additionally, G/G modules typically exhibit better thermal performance, as glass has a higher thermal conductivity than backsheets [14], facilitating more efficient heat dissipation. This characteristic can potentially lead to improved electrical performance under high-temperature conditions, although this advantage is still under investigation in the field. Moreover, the symmetrical structure of G/G modules allows for more uniform load distribution, reducing the risk of microcracks [15,16] and ensuring more reliable mechanical stability throughout their operational life.

However, there are also notable disadvantages to consider with G/G modules. For instance, they do not allow for the evaporation of internal EVA gases [17], which can lead to more degradation over time. Additionally, G/tB modules are generally lighter, making them easier to handle and install, which can be a significant practical advantage in certain applications. Furthermore, the market for transparent back sheets is still developing, and there are fewer commercial options available, which might impact supply and demand dynamics. In summary, while G/G bifacial modules offer robustness and efficiency, it is essential to consider both their advantages and disadvantages in comparison to G/tB modules to make an informed decision.

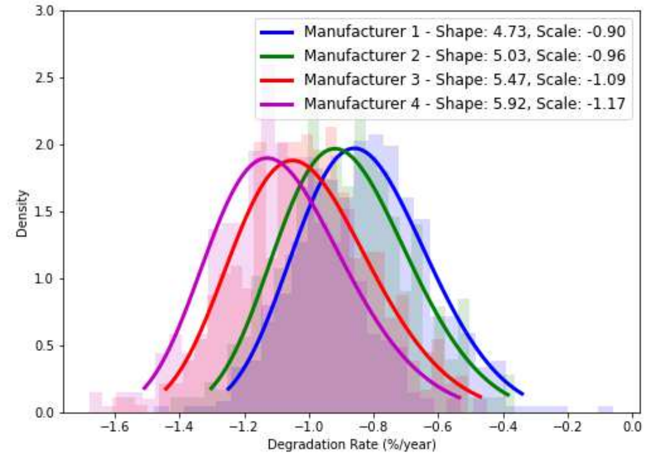

Fig. 3. Results of the G/G PV systems degradation rate.

C. Comparative Analysis of Bifacial vs Monofacial PV

In the third section of this analysis, we turn our attention to the comparative assessment of bifacial versus monofacial PV systems, with a particular focus on degradation rates as a crucial metric of long-term performance. Fig. 4 provides a distribution of degradation rates for an ensemble of monofacial PV systems, offering a consolidated view of their reliability and endurance in the field. The observed degradation rates for the monofacial systems from four different PV systems are -0.62%, -0.94%, -0.75%, and -0.86% per year, respectively.

The data suggests a notable trend: monofacial PV systems, on average, outperform their bifacial counterparts, specifically the G/tB and G/G systems previously discussed. This could potentially be attributed to the more mature technology and manufacturing processes associated with monofacial systems, which have been optimized over a longer period within the industry. The degradation rates for monofacial systems are closer to the industry benchmark of -0.7% per year [12], albeit still slightly higher. This comparison is particularly compelling given that the monofacial systems rates are derived from the same two-year operational period as the bifacial systems yet show a marked decrease in degradation.

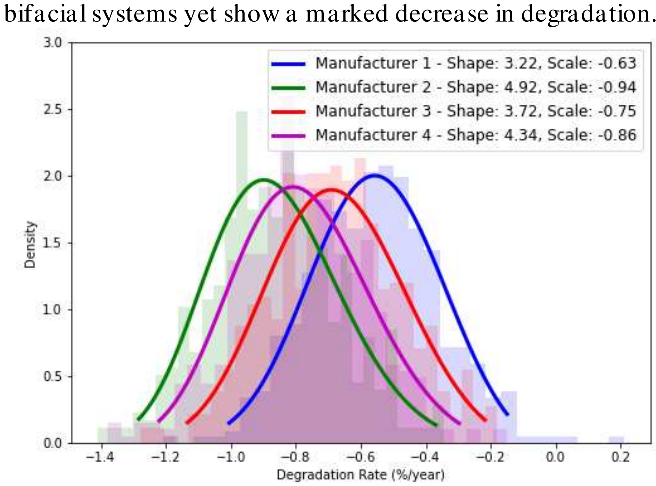

Fig. 4. Results of the monofacial PV systems degradation rate.

This article has been accepted for publication in IEEE Journal of Photovoltaics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JPHOTOV.2024.3414131

IV. Conclusion

Our analysis of eight bifacial PV systems over two years reveals critical insights into degradation rates and performance nuances between glass/transparent-backsheet (G/tB) and glass/glass (G/G) configurations, compared to traditional monofacial systems. G/tB systems in our study showed higher degradation rates, ranging from -1.46% to -2.30% annually, significantly surpassing the industry standard of -0.8%. Conversely, the G/G configurations demonstrated more moderate degradation rates between -0.90% and -1.17% per year, highlighting their superior durability and thermal efficiency based on our data. In comparison, the monofacial systems exhibited degradation rates closer to the industry benchmark, between -0.62% and -0.94%, indicating a current edge in long-term reliability over bifacial technologies.

It is important to note that these results are based on a specific set of systems and a limited operational period of two years. The degradation behavior observed in our study may not be representative of all bifacial G/G or G/tB systems. Additionally, while our focus has been on the impact of packaging materials, the evolution of bifacial cell technologies also plays a crucial role in degradation dynamics and should be considered in future studies. Additionally, this study underscores the potential of bifacial technologies in enhancing solar energy yield but also highlights the necessity of mitigating their higher degradation rates to achieve parity with monofacial system reliability. Continued research and development are essential to address these challenges and to realize the full potential of bifacial PV systems.

Acknowledgements

The authors wish to express their gratitude to Mr. Andy White of the University of York and Mr. Nick Olivier of Above Surveying Ltd. for their assistance in collecting the data and storing it on a suitable cloud platform. To process the extensive dataset from each PV installation, the Viking cluster was used during this project, which is a high-performance compute facility provided by the University of York, we are grateful for computational support from the IT Services and the Research IT team.

References

[1] E. Molin, B. Stridh, A. Molin and E. Wäckelgård, "Experimental Yield Study of Bifacial PV Modules in Nordic Conditions," in *IEEE J. Photovolt.*, vol. 8, no. 6, pp. 1457-1463, Nov. 2018.

[2] M. Dhimish and G. Badran, "Investigating defects and annual degradation in UK solar PV installations through thermographic and electroluminescent surveys," *npj Mater. Degrad.*, vol. 7, no. 1, pp. 14, 2023.

[3] S. Tsuchida, Y. Tsuno, D. Sato, T. Oozeki and N. Yamada, "Albedo-Dependent Bifacial Gain Losses in Photovoltaic Modules With Rear-Side Support Structures," in *IEEE J. Photovolt.*, vol. 13, no. 6, pp. 938-944, Nov. 2023.

[4] C. F. Abe, J. Batista Dias, G. Notton, G. -A. Faggianelli, G. Pigelet and D. Ouvrard, "Estimation of the Effective Irradiance and Bifacial Gain for PV Arrays Using the Maximum Power Current," in *IEEE J. Photovolt.*, vol. 13, no. 3, pp. 432-441, May 2023.

[5] J. Lopez-Garcia et al., "Implementation of the IEC TS 60904-1-2 Measurement Methods for Bifacial Silicon PV Devices," in *IEEE J. Photovolt.* vol. 12, no. 3, pp. 787-797, May 2022.

[6] M. Alam, M. S. Gul, and T. Muneer, "Performance analysis and comparison between bifacial and monofacial solar photovoltaic at various ground albedo conditions," *Renew. Energy Focus*, vol. 44, 2023, pp. 295-316.

[7] W. Mühleisen et al., "Energy yield measurement of an elevated PV system on a white flat roof and a performance comparison of monofacial and bifacial modules," *Renew. Energy*, vol. 170, 2021, pp. 613-619.

[8] G. Badran and M. Dhimish, "A Comparative Study of Bifacial versus Monofacial PV Systems at the UK Largest Solar Plant," in Clean Energy, Early access, May 2024.

[9] G. M. Tina et al., "Comparative analysis of monofacial and bifacial photovoltaic modules for floating power plants," *Appl. Energy*, vol. 281, 2021, Art. no. 116084.

[10] D. C. Jordan, C. Deline, S. R. Kurtz, G. M. Kimball and M. Anderson, "Robust PV Degradation Methodology and Application," in *IEEE J. Photovolt.*, vol. 8, no. 2, pp. 525-531, March 2018.

[11] A. A. Abdallah, K. Ali and M. Kivambe, "Performance and reliability of crystalline-silicon photovoltaics in desert climate," in *Solar Energy*, vol. 249, pp. 268-277, January 2023.

[12] D. C. Jordan, B. Marion, C. Deline, T. Barnes, and M. Bolinger, "PV field reliability status—Analysis of 100 000 solar systems," in *Progress in Photovoltaics: Research and Applications*, vol. 28, no. 8, pp. 739-754, March 2020.

[13] S. Smith, L. Perry, S. Watson, S. L. Moffitt, S. J. Shen, S. Mitterhofer, L. P. Sung, D. Jacobs and X. Gu, "Transparent backsheets for bifacial photovoltaic (PV) modules: Material characterization and accelerated laboratory testing," in *Progress in Photovoltaics: Research and Applications*, vol. 3, no. 8, pp. 959-969, October 2021.

[14] G. M. Tina, F. B. Scavo and A. Gagliano, "Multilayer Thermal Model for Evaluating the Performances of Monofacial and Bifacial Photovoltaic Modules," in *IEEE J. Photovolt.*, vol. 10, no. 4, pp. 1035-1043, July 2020.

[15] J. Lopez-Garcia et al., "Implementation of the IEC TS 60904-1-2 Measurement Methods for Bifacial Silicon PV Devices," in *IEEE J. Photovolt.*, vol. 12, no. 3, pp. 787-797, May 2022.

[16] A. Sinha, D. B. Sulas-Kern, M. Owen-Bellini, L. Spinella, S. Uličná, S. A. Pelaez, S. Johnston and L. T. Schelhas, "Glass/glass photovoltaic module reliability and degradation: a review," in *Journal of Physics D: Applied Physics*, vol. 5, no. 41, p. 413002, August 2021.

[17] C. Molto, J. Oh, F. I. Mahmood, M. Li, P. Hacke, F. Li, R. Smith, D. Colvin, M. Matam, C. DiRubio, and G. Tamizhmani, "Review of potential-induced degradation in bifacial photovoltaic modules," in *Energy Technology*, vol. 11, no. 4, p. 2200943, December 2023.