10 Years of Performance Findings at the Mineirão Stadium Solar Photovoltaic System

André M. Nobre[1], Juliano Marcial Fraga Fonseca[2], Clarissa D. Zomer[3], Rafael Corrêa Imbuzeiro[2] and Carlos Alberto Severiano Jr.[4]

[1] PV Doctor Pte. Ltd., Singapore (Singapore)

[2] Companhia Energética de Minas Gerais (CEMIG), Belo Horizonte (Brazil)

[3] Arquitetando Energia Solar, Florianópolis (Brazil)

[4] Instituto Federal de Minas Gerais (IFM), Belo Horizonte (Brazil)

Abstract

This study evaluates ten years (2014-2024) of operational data from the 1.42 MWp photovoltaic (PV) system at Mineirão Stadium, Belo Horizonte, Brazil. Using 3D shading simulations and empirical inverter outputs, we quantified sectional shading impacts, with south-facing segments showing up to 12% obstruction but system-wide energy losses limited to 2.8% annually. A -1.6%/year system degradation rate was derived using satellite irradiance and daily performance ratio methods, after excluding anomalies such as a 2020 transformer failure. Module-level IV curves confirmed lower DC-side degradation, highlighting inverter and soiling contributions. Maintenance challenges—particularly panel cleaning at height—were addressed via robotic systems. Results validate predictive modeling accuracy and demonstrate that urban PV retrofits in architecturally complex structures can achieve long-term performance with tailored O&M strategies, supporting scalable renewable integration in legacy infrastructure.

Keywords: solar PV, performance analysis, shading analysis, degradation, operational efficiency, urban PV

1. Introduction

Global photovoltaic (PV) capacity surpassed 2 TWp in 2024 (Global Solar Council, 2024), reflecting the rapid adoption of renewable energy worldwide amid falling costs and supportive policies. It took humanity approximately 68 years to reach 1 TWp of installed capacity (from 1954 to 2022), only to double it in two years by 2024 (International Renewable Energy Agency (IRENA), 2024), driven by unprecedented annual deployments exceeding 500 GWp. In Brazil, PV growth has been equally robust, with cumulative installed capacity projected to exceed 60 GWp by mid-2025 (pv-magazine.com), surpassing 50 GWp earlier that year, according to data from the Brazilian Photovoltaic Solar Energy Association (ABSOLAR, 2025).

In preparation for the 2014 FIFA World Cup, several Brazilian stadiums, including older venues, underwent significant retrofits to meet modern standards and accommodate international matches (Faria, 2014). The iconic Mineirão Stadium in Belo Horizonte, designed by renowned architect Oscar Niemeyer and opened in 1965, was among them, receiving a major upgrade that included a 1.42 MWp photovoltaic system operational since May 2014. Located in the scenic Pampulha region beside the city’s renowned lagoon, a UNESCO World Heritage site celebrated for its modernist architecture and natural beauty, this more than 60-year-old landmark faced unique operational challenges, particularly shading from its distinctive curved façade, which reduces energy production.

This study delivers a thorough examination of the Mineirão Stadium PV system’s decade-long performance, from 2014 to 2024. Employing advanced 3D shading modeling, it quantifies anticipated energy losses across diverse roof segments (see Figure 1), rigorously validated against empirical inverter output data to confirm predictive accuracy. Complementary aging analyses gauge overall system degradation rates while incorporating granular single-module assessments to pinpoint variability. Despite persistent challenges like shading and maintenance demands, the system's consistent energy yield affirms the viability of retrofitting building-integrated PV into legacy urban structures, furnishing actionable lessons for scaling renewables in densely populated areas and bolstering worldwide efforts toward net-zero emissions.

10.18086/swc.2025.08.01 Available at http://proceedings.ises.org

Figure 1: Aerial view of the Mineirão Stadium photovoltaic (PV) system, featuring 5,910 solar modules spanning 9,500 m² of the stadium's roof in Belo Horizonte, Brazil.

2. Methodology

This study is structured in two parts to comprehensively analyze the Mineirão Stadium PV system's performance. In Part 1, we employ 3D modeling software to simulate the stadium's architecture, evaluating shading impacts across various roof sections, considering azimuth and tilt angle combinations, and accounting for seasonal variations throughout the year. Model validation is achieved by comparing simulated results with empirical power output data from inverters in selected sections. In Part 2, we assess system degradation trends, analyzing performance at both the full-system level and through detailed module-level measurements to quantify aging effects accurately.

Part 1: Shading Modelling & Assessment

A comprehensive shading assessment was conducted to evaluate obstructions affecting the photovoltaic (PV) array's energy yield at Mineirão Stadium. A detailed 3D model was constructed using SketchUp and Revit, integrating architectural drawings, site photographs, and Google Earth imagery as primary inputs. The consolidated model was exported in OBJ and IFC formats for advanced analysis in PD Shading Box and BIMsolar, respectively (see Figure 2). This approach enabled precise quantification of shading impacts across the PV system's roof segments, enhancing performance predictions.

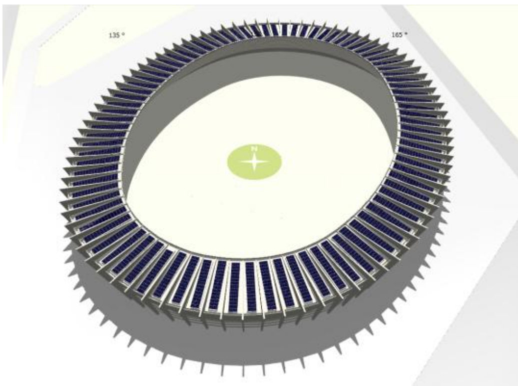


Figure 2: 3D Model of the Mineirão Stadium.

Solar irradiance and shading impacts were evaluated using two advanced tools: (i) obstruction ("shading") masks generated via Andrew Marsh's PD Shading Box platform [Marsh 2005, Marsh 2017], and (ii) BIMsolar, a specialized simulation environment for building-integrated photovoltaics (BIPV) (BIMsolar 2025, EnerBIM

2025). For traceability, PV modules were systematically numbered as depicted in Figure 3, with specific segments highlighted in gray for analysis: Segments #4 and #5 (west side), #21 and #22 (south side), #49 and #50 (east side), and #66 and #67 (north side). This structured approach enabled precise assessment of shading effects across the Mineirão Stadium PV system's roof segments.

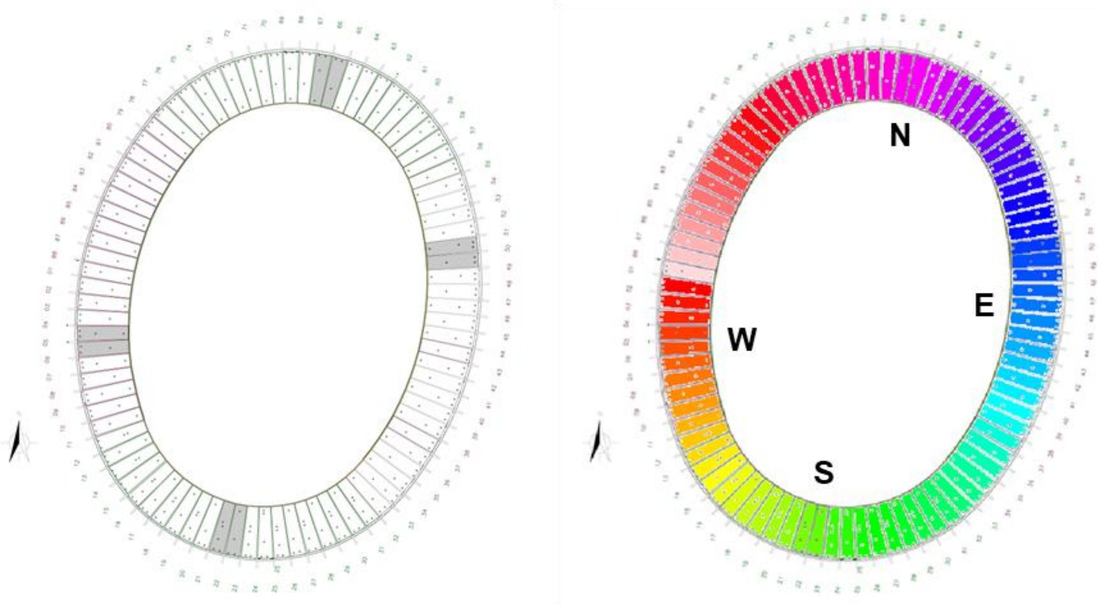


Figure 3: Left – Selected segments for shading analysis (in gray), covering west (4/5), south (21/22), east (49/50) and north (66/67). Right – Color scheme for each of the 88 segments of the Mineirão Stadium.

Shading impacts on the Mineirão Stadium PV system were analyzed using PD Shading Box and BIMsolar simulations. Using PD Shading Box, shading masks were generated for multiple positions across the PV array to quantify the annual proportion of sunlit versus shaded periods for each module (Zomer 2014; Zomer 2016; Zomer 2017a; Zomer 2017b). Three vertical positions (top, middle and bottom, see Figure 4) were evaluated within representative segments (#4–5 west, #21–22 south, #49–50 east, #66–67 north) to capture intra-row variations. In BIMsolar, the IFC model was imported, configured with the site's location and a 20% surface albedo. MPrime M240P PV modules were then positioned on the 3D geometry, aligning with the project's design, to simulate performance under site-specific conditions.

Figure 4: Vertical sections chosen for shading evaluation (top, middle and bottom).

To evaluate the accuracy of the shading model, AC power output data from the photovoltaic (PV) system across eight highlighted segments of the Mineirão Stadium were analyzed. Data from a single calendar year were examined, with one clear-sky day per month in 2015 selected for detailed study (see Figure 5 for 12-Feb-2015). This figure illustrates the AC power output of all eight inverters on that day, with each segment represented by a distinct graph color. Outputs from eight specific inverters, corresponding to segments #4–5 (west), #21–22 (south), #49–50 (east), and #66–67 (north), were compared to quantify energy gains and losses across the year, validating the model's predictions.

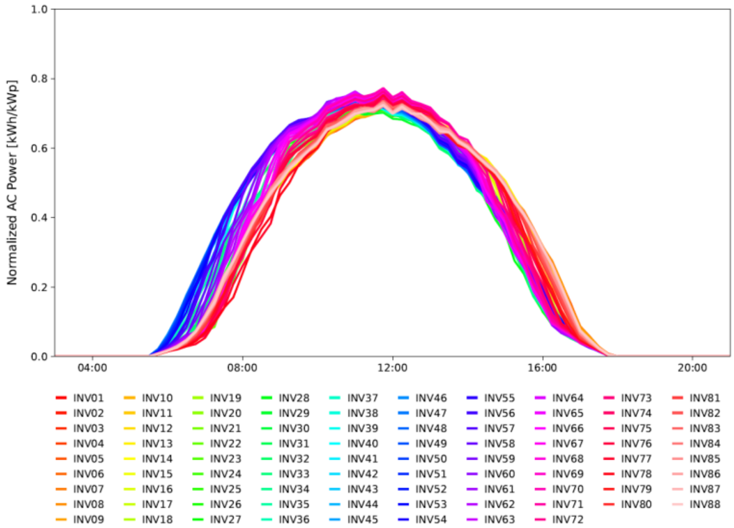


Figure 5: Following the color pattern of Figure 3 (Right), the normalized power AC output for the 88 inverters at the Mineirão PV system is illustrated for a clear-sky day in February.

Part 2: System Ageing & Degradation Analysis

This study assesses the performance of the Mineirão Stadium's 1.42 MWp photovoltaic (PV) system over its initial decade of operation, from May 2014 to May 2024. Monthly energy generation data, covering over 120 months, were analyzed using degradation calculation methods previously validated for Asian PV systems (Nobre, 2013; Nobre, 2023). Figure 6 depicts the monthly generation trend, highlighting early "teething" challenges, which encompass issues during setup, commissioning, and initial months of operation. A notable transformer failure disrupted output for four months in 2020, necessitating exclusion of such operational anomalies to accurately assess degradation. While preliminary analysis indicated system aging, refined calculations in this section using daily performance ratio (as shown in Nobre, 2013) are necessary to understand long-term performance decline.

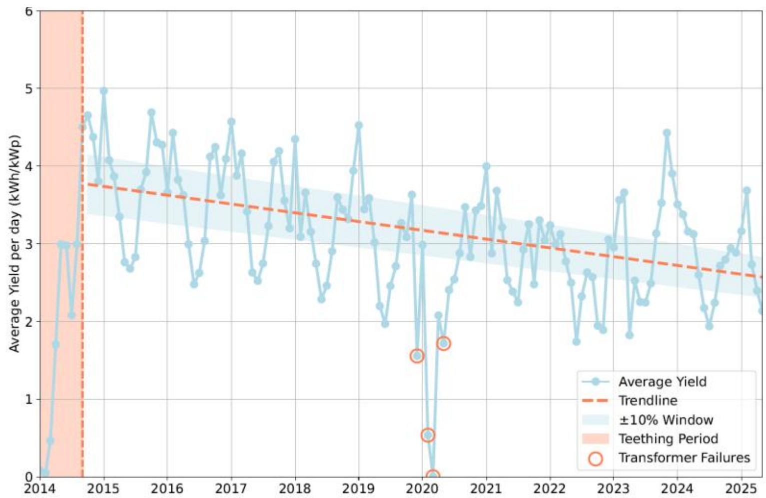


Figure 6: Average daily energy yield generation of the Mineirão Stadium's 1.42 MWp PV system plotted monthly from 2014 to 2024, highlighting operational challenges, including a four-month transformer failure in 2020, and illustrating progressive system degradation over the decade.

To further validate the performance degradation of the stadium's PV system, a secondary method employed IV curve tracer equipment (HT Instruments, I-V600) to measure electrical characteristics across multiple segments of the system. Measurements were conducted at approximately ~11.5 years of life of the system. This approach, complementing the daily generation analysis provides detailed insights into module-level degradation across the system lifetime.

3. Results

Part 1: Shading Modelling & Assessment

Shading Masks

Shading masks were generated for eight selected positions across the stadium's PV system, corresponding to segments #4–5 (west), #21–22 (south), #49–50 (east), and #66–67 (north). As adjacent segments displayed comparable shading patterns, they were grouped in Figure 7. Each mask depicts the annual solar exposure distribution across the sky dome for its respective position, quantifying the proportion of time each module is sunlit or shaded.

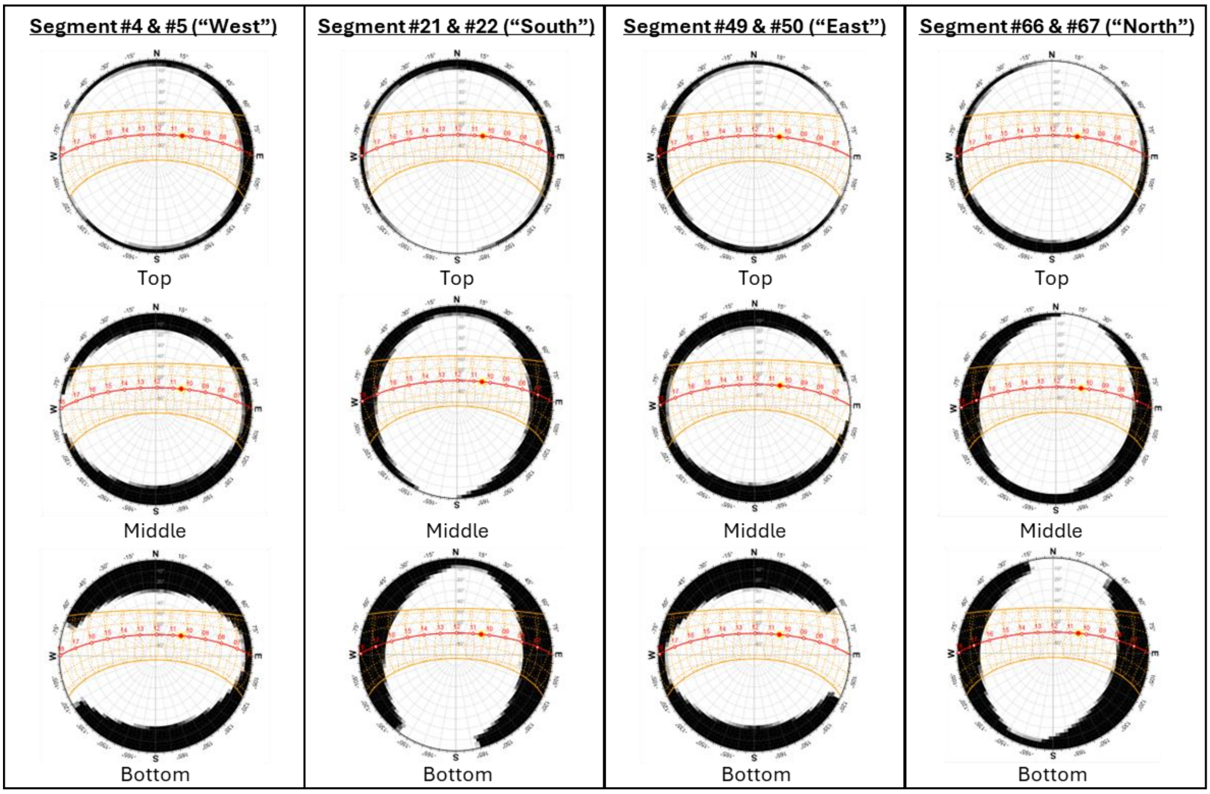


Figure 7: Shading masks for the selected segments.

According to the shading masks, the bottom portions were the most affected across all orientations. Some positions were mainly influenced by diffuse sky obstruction and remained largely free from direct-beam shading (segments #4 and #5 on the west, and #49 and #50 on the east). In contrast, the south and north-facing segments experienced more direct-beam shading, with the corresponding shaded time windows as follows:

- #21, #22 — until approximately 08:00 and after 16:00 throughout the year.
- #66, #67 — until approximately 08:00 and after 16:30 throughout the year.

The overcast-sky shading values for each segment are presented in Table 1.

Table 1: Overcast sky shading for selected segments.

Mineirão Shading Analysis		Overcast Sky Shading		
Segments	**Orientation**	**Bottom**	**Center**	**Top**
#4	west	19.9%	12.2%	5.0%
#5	west	19.5%	12.2%	5.2%
#21	south	19.5%	12.9%	4.4%
#22	south	19.9%	13.3%	4.6%
#49	east	19.0%	11.7%	4.5%
#50	east	18.4%	11.4%	4.6%
#66	north	20.2%	13.5%	3.9%
#67	north	21.2%	13.0%	4.3%
Average		19.7%	12.5%	4.6%
Total Average		12.3%		

BIMsolar Simulations

BIMsolar analysis presents the shading energy yield losses for each PV module. The results for the selected segments are shown in Figure 8.

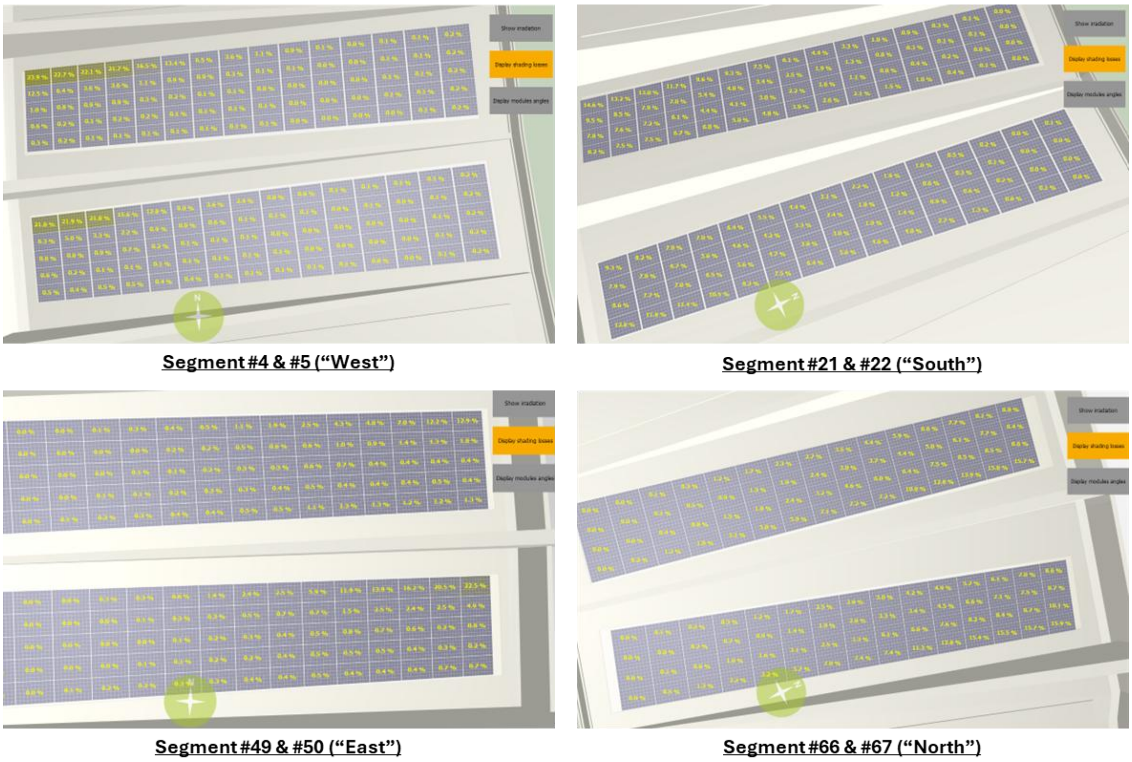
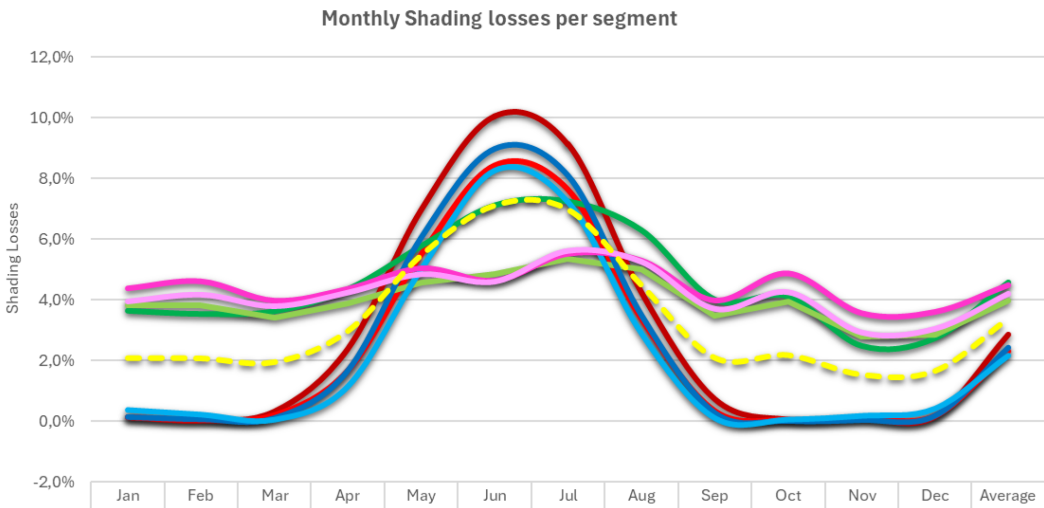


Figure 8: Annual shading losses in each PV module according to BIMsolar's analysis.

The average shading losses for each segment are presented on a monthly basis in Figure 9. While certain losses may account to more than 10% (see segment #4, facing west for June), overall losses ranged from 1.1% to 4.9% for the entire year. According to BIMsolar's analysis, the average annual energy yield loss due to shading is approximately 2.8%, which is significantly lower than the 12.26% average overcast-sky shading. This difference indicates that not all periods of geometric or diffuse shading result in measurable energy losses. Most of the shaded intervals occur during early morning or late afternoon, when the incident irradiance and power output are relatively low. Consequently, the overall impact on system performance remains limited.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
#4	0,1%	0,0%	0,3%	2,4%	7,0%	10,1%	9,1%	4,2%	0,7%	0,1%	0,1%	0,2%	2,9%
#5	0,1%	0,0%	0,2%	1,7%	5,5%	8,4%	7,6%	3,4%	0,3%	0,0%	0,1%	0,2%	2,3%
#21	3,6%	3,5%	3,6%	4,4%	5,8%	7,1%	7,3%	6,3%	4,0%	4,1%	2,5%	2,7%	4,6%
#22	3,8%	3,8%	3,4%	3,9%	4,6%	4,9%	5,4%	5,0%	3,5%	3,9%	2,8%	2,8%	4,0%
#49	0,2%	0,1%	0,1%	1,7%	6,1%	9,0%	8,1%	3,5%	0,3%	0,0%	0,1%	0,2%	2,4%
#50	0,4%	0,2%	0,1%	1,2%	5,0%	8,3%	7,2%	2,9%	0,1%	0,1%	0,2%	0,4%	2,2%
#66	4,4%	4,6%	4,0%	4,4%	5,0%	4,6%	5,5%	5,3%	4,0%	4,9%	3,6%	3,6%	4,5%
#67	3,9%	4,2%	3,8%	4,2%	4,8%	4,6%	5,6%	5,3%	3,7%	4,2%	2,9%	3,0%	4,2%
Average	2,1%	2,1%	1,9%	3,0%	5,5%	7,1%	7,0%	4,5%	2,1%	2,2%	1,5%	1,6%	3,4%

Figure 9: Monthly shading losses in average for each segment according BIMSolar's analysis and the entire site average.

Detected Empirical Shading Losses

Using inverter outputs from the eight selected stadium segments, we identified the day with the best irradiance profile (least cloud cover and closest to clear-sky conditions, as exemplified in Figure 5) for each month of 2015. Since shading simulations confirmed that east-facing segments experiencing the least obstruction, we normalized all readings to the east as the baseline. As shown in Table 2, the north section underperformed by 0.7%, the west by 3.6%, and the south—being the most shade-prone—exhibited the largest deficit relative to the east-facing segments.

Table 2: Inverter performance on twelve clear-sky days in 2015.

	West	South	East	North
Jan	1.3%	-9.2%	0.0%	-5.5%
Feb	-1.7%	-6.6%	0.0%	-8.9%
Mar	-7.2%	-15.5%	0.0%	-12.7%
Apr	-3.6%	-10.4%	0.0%	1.8%
May	-1.7%	-8.1%	0.0%	17.5%
Jun	-4.3%	-6.9%	0.0%	27.3%
Jul	-4.7%	-8.2%	0.0%	24.6%
Aug	-4.0%	-9.1%	0.0%	14.4%
Sept	-3.2%	-15.5%	0.0%	-5.1%
Oct	-5.6%	-11.9%	0.0%	-6.9%
Nov	-6.2%	-8.3%	0.0%	-9.9%
Dec	-3.0%	-3.8%	0.0%	-8.1%
AVG	**-3.6%**	**-9.5%**	**0.0%**	**-0.7%**

Part 2: System Ageing & Degradation

To assess long-term system performance, we calculated the daily Performance Ratio (PR). Due to limitations in local sensor data—primarily the need for continuous cleaning and data availability of instruments—we relied on third-party satellite irradiance data, following the methodology established by Nobre (2023). PR values above 90% or below 20% were excluded as outliers. Additionally, we applied Nobre's (2013) filtering protocol to remove non-stable operating conditions. Approximately 83% of the original data points remained after filtering. The resulting analysis revealed an annual degradation rate of -1.6%, as shown in Figure 10.

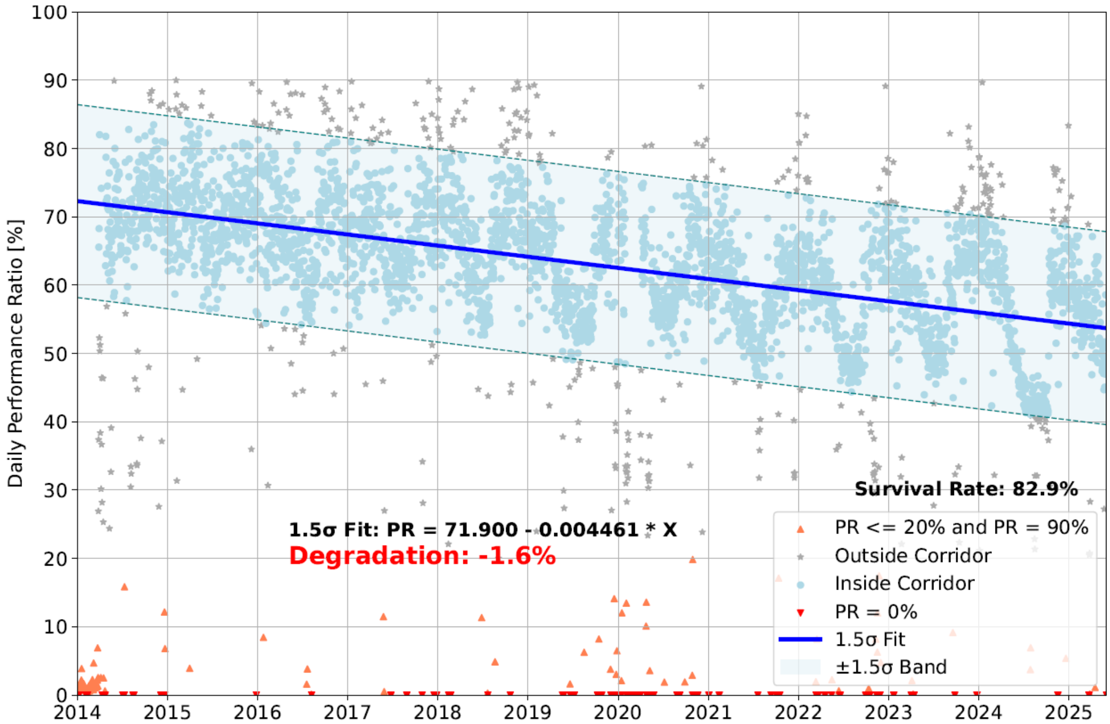


Figure 10: Daily performance ratio evolution for the Mineirão Stadium across more than a decade of operations. A degradation of -1.6% per annum has been observed.

Continuing on other performance field checks, IV curves were performed at strings of the system. Figure 11 shows the "box-and-whisker" plot for the measurements at the four system sections under study. The average across 46 tested strings in total indicated a deviation of -11.6%, which in turn, given the time between system start-up and measurement date of 11.7 years, indicates a module/string degradation of circa -1.0% per year.

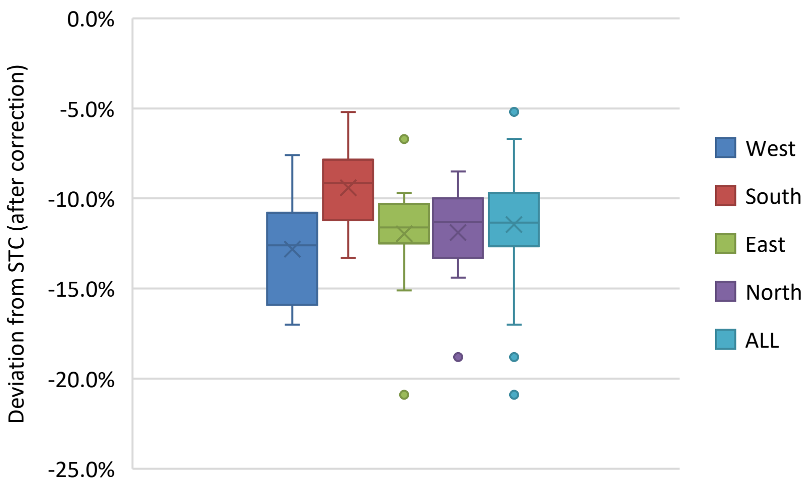


Figure 11: Box-and-whisker plot for IV string measurements at the four system sections under study at the Mineirão Stadium.

4. Discussions

BIMsolar simulations reveal an average 2.8% reduction in annual energy yield due to shading across the entire system. While overcast-sky analysis indicates an average shading factor of 12.26%, its impact on actual energy production is significantly lower. This discrepancy arises because most modules remain fully illuminated year-round, with only lower-tier panels and those near structural beams experiencing partial obstruction. The inverted structural beams are the primary shading source, intermittently blocking adjacent modules. These findings underscore that geometric shading in sky-dome models does not directly correlate with energy losses, highlighting the critical need to integrate both geometric and energy-based assessments for accurate BIPV performance evaluation.

The iconic façade of Mineirão Stadium raised early concerns about shading losses in photovoltaic integration. However, validated simulations and empirical data confirm that these losses are both quantifiable and manageable within the constraints of a retrofit project. This outcome validates the feasibility of complex BIPV/BAPV applications, demonstrating that even challenging architectural integrations can achieve successful energy performance.

The empirical shading analysis in this study relied on twelve clear-sky, high-irradiance days. Shading patterns under cloudless conditions differ markedly from those during partially cloudy or rainy periods. A valuable extension of this work would involve calculating shading losses across diverse irradiance regimes to better reflect real-world performance at Mineirão.

Cleaning the solar arrays poses a significant operational challenge due to the height and limited water access at the stadium roof. Traditional cleaning is complex, costly, and logistically demanding. In response, robotic cleaning systems have been recently deployed (see Figure 12), improving both speed and consistency of soiling removal.

Figure 12: Left – Water access constraints complicate manual cleaning at the top of Mineirão Stadium. Right – Robotic cleaning systems now enhance efficiency and quality.

Maintenance difficulties with on-site sensor cleaning and uptime have compromised the reliability of local irradiance data for performance ratio (PR) calculations. To address this, third-party satellite data (source: Solargis) was used to generate Figure 10, following a methodology proven effective in prior studies. Figure 13 validates this approach by comparing satellite-derived global horizontal irradiance (GHI) with measurements from a nearby INMET meteorological station (~500 m away at UFMG). The strong correlation ($R^2 = 0.981$ over multiple years) confirms the robustness of satellite data for long-term performance trending utilization.

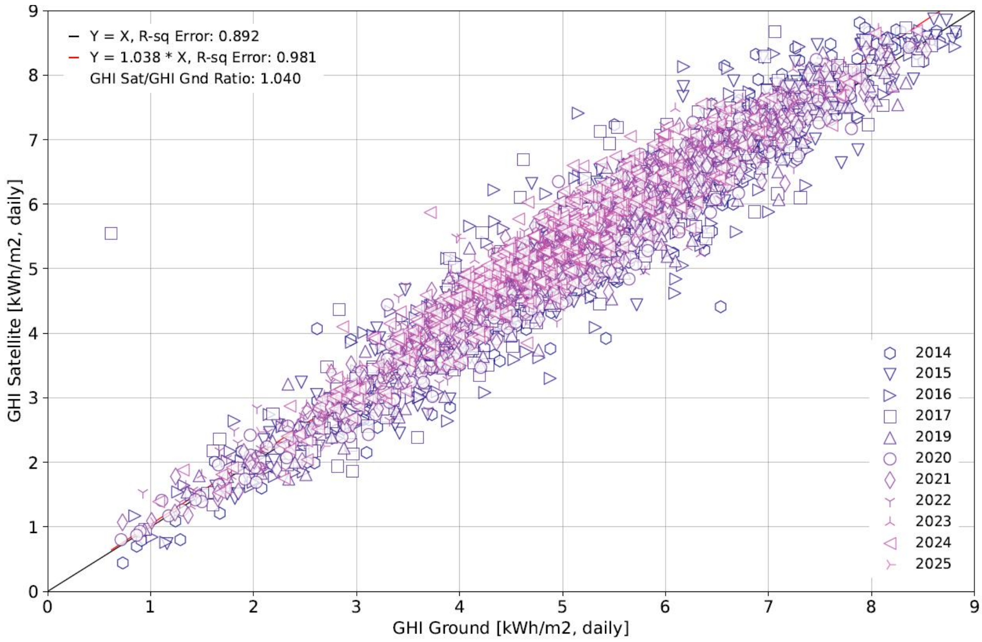


Figure 13: Scatter plot of satellite global horizontal irradiation data from Mineirão vs. data from an INMET meteorological station at Universidade Federal de Minas Gerais (UFMG, ~500 m away).

The reported -1.6% per annum degradation rate reflects system-wide performance, encompassing losses from modules through inverters. This should not be interpreted as individual panel degradation, which requires laboratory STC testing for warranty validation. As shown in Figure 11, IV curve measurements on DC strings indicate lower degradation rates. The broader system-level figure includes inverter efficiency drift, wiring losses, and soiling—factors absent in isolated module tests—highlighting the importance of context when evaluating performance claims.

5. Conclusions

The decade-long performance analysis of the Mineirão Stadium PV system demonstrates that urban BIPV retrofits can deliver robust, predictable energy yields despite complex architectural constraints. Shading simulations, validated by empirical inverter data, revealed manageable losses of 2.8% annually, with south-facing sections experiencing up to 12% obstruction—yet most modules remained fully productive. The system-level degradation rate of -1.6% per annum slightly exceeds typical values but reflects real-world factors including soiling, inverter drift, and maintenance limitations, and not isolated module failure. These findings affirm that geometric shading does not equate to proportional energy loss, emphasizing the value of integrated 3D modeling and field validation.

As Mineirão solar PV system enters its second decade, targeted maintenance innovations—such as robotic cleaning—and satellite-based performance monitoring have proven essential for operational resilience. This pioneering installation validates the technical and economic viability of large-scale PV integration into iconic legacy structures, offering a scalable model for urban decarbonization. Future efforts should prioritize adaptive O&M protocols and multi-condition shading studies to further optimize BIPV performance in challenging environments.

6. Acknowledgments

A.M. Nobre acknowledges the support of Dr. Xiaoqi XU (from the Solar Energy Research Institute of Singapore, SERIS, at the National University of Singapore, NUS). Additionally, thanks are extended to Anamika Singh and Manav Gupta from PV Doctor for certain analyses support. A special acknowledgement to Journalist Oswaldo Nobre, who first took the author to the Mineirão Stadium as a kid.

J.M.F. Fonseca would like to thank the Companhia Energética de Minas Gerais (CEMIG) for the opportunity to work on this topic and present it at an international scientific event. Further thanks are extended to Minas Arena – Mineirão for the data availability as well as in situ hosting opportunities for the involved personnel.

7. References

ABSOLAR, 2025. Infográfico do Mercado Solar Brasileiro 2025. https://www.absolar.org.br/mercado/infograficos/ (accessed October 20, 2025).

BIMsolar. *The most efficient way to design, feature and integrate BIPV modules*. 2025 [accessed in 04/09/2025; Available from: https://pim.bim-solar.com/.

EnerBIM, *BIMsolar*. 2025.

Faria, L.C., 2014. Sustainable retrofits of Brazilian stadiums for the 2014 FIFA World Cup: Challenges and opportunities, in: Proceedings of the International Conference on Sustainable Infrastructure, Rio de Janeiro, 10-12 June. ASCE, pp. 145-156. DOI: 10.1061/9780784413517.015.

Global Solar Council, 2024. Global Market Outlook for Solar Power 2024-2028. https://globalsolarcouncil.org/wp-content/uploads/2024/06/Global-Market-Outlook-for-Solar-Power-2024-2028.pdf (accessed October 20, 2025).

International Renewable Energy Agency (IRENA), 2024. Renewable Capacity Statistics 2024. https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024 (accessed October 20, 2025). DOI: 10.1787/renewable-capacity-2024-en.

Marsh, A. PD: Shading Box. 2017 [accessed in 02/09/2025]; Available from: https://andrewmarsh.com/apps/staging/shading-box.html.

Marsh, A. THE APPLICATION OF SHADING MASKS IN BUILDING SIMULATION. Ninth International IBPSA Conference. 2005. Montreal, Canada.

Nobre, A., Malhotra, R., Tang, C.H., Reise, C., Kiefer, K., Rüther, R., Reindl, T., 2013. Degradation Analysis of Photovoltaic Systems in a Tropical Environment, in: Proceedings of the 28th European Photovoltaic Solar Energy Conference and Exhibition, Paris, France, 30 September–4 October 2013. WIP Renewable Energies, Munich, Germany. DOI: 10.4229/28thEUPVSEC2013-5CO.5.4.

Nobre, A.M., Pakdeepinyo, T., Ward, J., Jaswal, R., Pranav, S., Chouhan, S.S., Gaurav, A., Sharma, A.K., 2023. The Early Death of PV Systems in Asian Sites Set in Industrial Areas, in: Proceedings of the 40th European Photovoltaic Solar Energy Conference and Exhibition, Lisbon, Portugal, 18–22 September 2023. WIP Renewable Energies, Munich, Germany, pp. 020307-001–020307-007. DOI: 10.4229/EUPVSEC2023/4BO.7.5.

Zomer, C., et al., The balance between aesthetics and performance in building-integrated photovoltaics in the tropics. Progress in Photovoltaics: Research and Applications, 2014. 22(7): p. 744-756.

Zomer, C., et al., Shading analysis for rooftop BIPV embedded in a high-density environment: A case study in Singapore. Energy and Buildings, 2016. 121: p. 159-164.

Zomer, C. and R. Rüther, Simplified method for shading-loss analysis in BIPV systems – part 1: Theoretical study. Energy and Buildings, 2017. 141: p. 69-82.

Zomer, C. and R. Rüther, Simplified method for shading-loss analysis in BIPV systems. Part 2: Application in case studies. Energy and Buildings, 2017. 141: p. 83-95.