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LONG-TERM PERFORMANCE ASSESSMENT OF MULTIPLE PHOTOVOLTAIC TECHNOLOGIES NEAR THE EQUATOR

Summary

This study presents a comprehensive long-term performance assessment of eight photovoltaic (PV) module technologies in a subtropical desert environment near the equator (Lima, Peru). Over five years, the performance of crystalline silicon (c-Si) and thin-film modules was evaluated through measured outdoor I-V curves. Results reveal significant climatic impacts, with thermal and spectral variations affecting the Module Performance Ratio (MPR). The c-Si modules experienced thermal losses between -2.7% and -4.3%, while thin-film modules ranged from -2.2% to -2.6%. Spectral variations induced losses in mono-Si modules between -0.7% and -1.5%, yet an amorphous silicon module exhibited spectral gains of +5.7%. Using an ensemble statistical approach, we derived consistent Performance Loss Rates (PLRs), with c-Si modules showing degradation rates from -0.9% to -1.6% per year. Comparative benchmarking identifies the HIT module as demonstrating superior long-term performance relative to newer IBC and PERT modules.

Keywords: Photovoltaic technologies, Outdoor I-V measurements, Long-term performance, Performance Loss Rate, Spectral impacts, Thermal impacts

1. Introduction

Global solar photovoltaic (PV) capacity reached 2.2 TW in 2024, marking rapid expansion and technological diversification. Accelerated deployment demands accurate prediction of module reliability and lifespan to ensure continued confidence among users and investors. Field performance assessments directly inform predictive models, standards, and accelerated testing methods, crucial for reliability in large-scale PV systems. However, there are significant research gaps concerning the impact of climatic conditions, especially at low latitudes and in the Southern Hemisphere. Most existing long-term studies have focused on mid-latitude regions, leaving areas near the equator understudied despite their distinct thermal and spectral environments. Performance Loss Rate (PLR) analysis captures reversible and irreversible module degradation effects, essential for lifespan prediction and maintenance strategies. Nonetheless, traditional linear PLR models often inadequately represent complex degradation processes occurring under diverse environmental stresses. Recently, the ensemble statistical approach combining various PLR models and performance metrics has emerged as a robust method for long-term PV performance analysis. This research addresses these gaps by assessing eight c-Si and thin-film-based PV module technologies over five years in Lima, Peru, employing comprehensive climatic corrections to account for performance losses and robust statistical analyses.

2. Experimental Setup

This study used data from an outdoor photovoltaic research laboratory located in Lima, Peru, characterized by a subtropical desert climate. This laboratory, situated in a subtropical desert environment, is equipped for detailed meteorological and photovoltaic performance monitoring (Fig. 1). The climate is characterized by relatively lower average temperatures than typical hot desert climates, accompanied by high humidity and frequent cloudy conditions. Eight photovoltaic technologies were evaluated: five crystalline silicon (c-Si) technologies (Al-BSF, HIT, PERT, IBC, PERC) and three thin-film technologies (a-Si/μc-Si, a-Si, and CIGS). These modules were installed facing north with a 20° tilt to balance sunlight exposure and minimize dust accumulation. The modules were regularly cleaned to reduce performance losses from soiling.

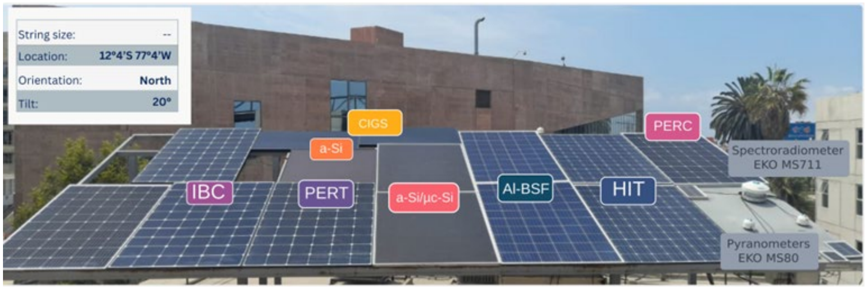

Fig. 1: Performance and reliability system at the Outdoor Photovoltaic Research Laboratory.

Performance data were collected using synchronized measurement equipment that included broadband and spectral irradiance sensors, ambient temperature sensors, and I-V curve tracers. The I-V tracing system employed a capacitive load setup with low measurement uncertainty, accurately capturing the performance characteristics of each module. This system recorded comprehensive I-V curves every five minutes, aligned with meteorological data collection. The analysis employed climatic corrections using standard methods from IEC guidelines for temperature and spectral mismatch adjustments. Performance metrics analyzed included Module Performance Ratio (MPR), Effective Nominal Power, Module Performance Index (MPI), and Performance Loss Rate (PLR). These metrics provided a robust evaluation of module performance under real operating conditions, accounting for both reversible climatic impacts and irreversible degradation phenomena. An ensemble statistical approach was adopted to determine PLR, combining various statistical methods and performance metrics to generate reliable long-term degradation estimates. This approach helped in benchmarking the different module technologies and assessing their comparative long-term performance reliability in the given climatic context.

3. Results and Discussion

Significant climatic impacts on photovoltaic (PV) performance were observed, notably due to variations in module temperature and spectral distribution, shown in Fig. 2. Thermal influences led to MPR losses between -2.7% and -4.3% for c-Si modules, with the PERT technology demonstrating the highest thermal sensitivity. Thin-film modules exhibited lower thermal losses ranging from -2.2% to -2.6%. Spectral influences further differentiated module performance, inducing losses between -0.7% and -1.5% in c-Si modules, particularly impacting HIT technology. The amorphous silicon (a-Si) module shows significant spectral gains of +5.7%.

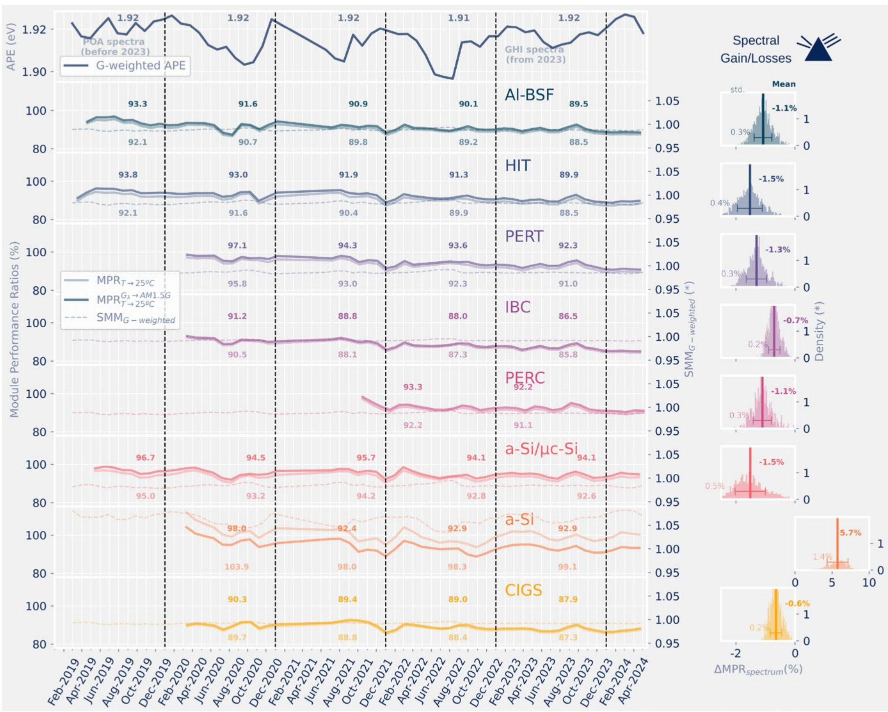

Fig. 2: MPR corrected by temperature and spectrum, along with the irradiance-weighted Spectral Mismatch Factor (SMM).

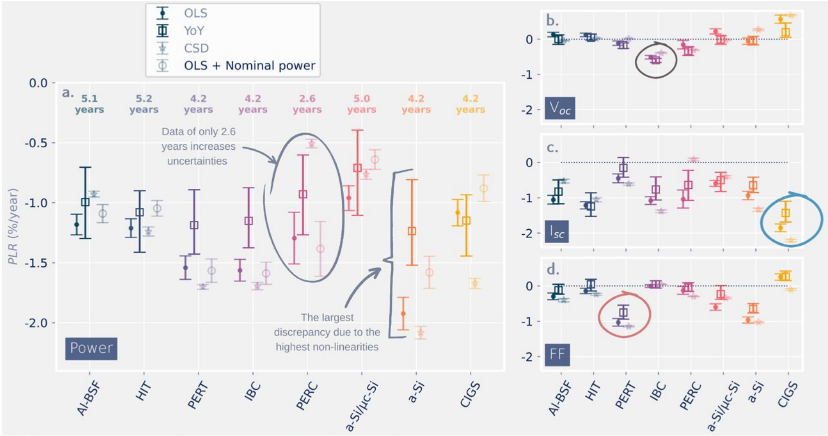

Fig. 2: MPI-based PLRs using the OLS, YoY, and CSD methods for the (a) power, (b) V_{oc}, (c) I_{sc}, and (d) FF.

In Fig. 2., Performance Loss Rates (PLRs) evaluated for up to five years revealed module-specific degradation patterns. The c-Si modules displayed annual degradation rates varying between -0.9% and -1.6%. PLR analyses for specific electrical parameters revealed minimal changes in open-circuit voltage (V_{oc}), generally stable performance in short-circuit current (I_{sc}), and significant variations in the Fill Factor (FF). For instance, the IBC module experienced substantial V_{oc} degradation, likely associated with deteriorations in cell passivation. In contrast, the CIGS module showed minimal V_{oc} and FF losses but notable current losses, potentially due to cell-level current mismatch phenomena. The PERT module demonstrated pronounced FF losses, likely driven by increased series resistances affecting overall performance.

Modules	Rated Efficiency (%)	4-y MPR | CI (%)	$\Delta MPR_{temperature}$ | CI(%)	$\Delta MPR_{spectrum}$ | CI(%)	Approx. ΔMPR_{others} (%)	$\overline{PLR}$ | CI(%/year)
5+ years Al BSF	16.5	86.76 [86.51, 87.01]	-4.16 [-4.31, -4.01]	-1.08 [-1.10, -1.07]	-5.8	-0.99 [-1.04, -0.94]
5+ years HIT	19.7	88.68 [88.49, 88.88]	-2.84 [-2.94, -2.73]	-1.53 [-1.55, -1.50]	-4.5	-1.13 [-1.18, -1.09]
4+ years PERT	20.1	89.14 [88.89, 89.39]	-4.27 [-4.43, -4.11]	-1.30 [-1.32, -1.28]	-1.3	-1.61 [-1.64, -1.58]
4+ years IBC	21.4	85.37 [85.17, 85.57]	-2.71 [-2.83, -2.61]	-0.71 [-0.72, -0.69]	-7.4	-1.59 [-1.64, -1.55]
2+ years PERC	19.3	88.50 [88.23, 88.79]	-3.66 [-3.82, -3.49]	-1.12 [-1.14, -1.1]	-5.8	-0.90 [-0.98, -0.83]
5+ years a-Si/μc-Si	9.0	91.80 [91.63, 91.97]	-2.24 [-2.32, -2.15]	-1.51 [-1.54, -1.49]	-2.8	-0.69 [-0.75, -0.62]
4+ years a-Si	12.9	97.22 [96.98, 97.47]	-2.63 [-2.73, -2.53]	5.72 [5.64, 5.81]	-2.7	-1.30 [-1.38, -1.22]
4+ years CIGS	14.3	85.92 [85.76, 86.08]	-2.44 [-2.53, -2.35]	-0.65 [-0.66, -0.63]	-8.3	-1.10 [-1.15, -1.04]

Fig. 3: Benchmarking long-term PV module performance in a daily aggregation table.

Benchmarking performance in Fig. 7 identified the HIT module (released in 2016) as demonstrating superior long-term performance compared to newer technologies, such as IBC (2018) and PERT (2019). This highlights that earlier-generation modules may sustain competitive long-term performance under specific climatic conditions. Thus, module selection for PV system deployment should consider both climatic factors and long-term reliability metrics.

4. References

Quest, H., Ballif, C., Virtuani, A., 2024. Intrinsic performance loss rate: Decoupling reversible and irreversible losses for an improved assessment of photovoltaic system performance. Prog Photovolt Res Appl. 32, 774-789

Mirletz, H., Ovaitt, S., Sridhar, S., Barnes, T. M., 2024. Prioritizing circular economy strategies for sustainable PV deployment at the TW scale. EPJ Photovoltaics. 15, 18.

Lindig, S., Theristis, M., Moser, D., 2022. Best practices for photovoltaic performance loss rate calculations. Prog. Energy, 4.