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FIFTEEN YEARS UNDER THE SUN: REAL-FIELD DEGRADATION ANALYSIS OF VETERAN PV MODULES

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ABSTRACT: This study presents a 15-year performance analysis of photovoltaic (PV) modules installed at CEA's outdoor test site in Cadarache, southern France. Three PV technologies – polycrystalline silicon (p-Si), amorphous silicon (a-Si), and monocrystalline silicon (m-Si) – have been continuously monitored under real-field conditions to assess their long-term degradation rates and aging mechanisms. The p-Si modules exhibited the highest degradation rate, averaging 2% per year, significantly exceeding the manufacturer's warranty expectations of 0.8% per year. Laboratory flash tests confirmed power losses ranging between -33% and -70% over 15 years. Infrared (IR) imaging identified a single hot spot, but degradation appeared uniformly distributed across all modules. Electroluminescence (EL) analysis revealed extensive microcracks and inactive cell regions, while visual inspections highlighted discoloration, light corrosion, and early signs of delamination. Despite these findings, no critical failures were detected in bypass diodes or electrical connectors. The study underscores the necessity of long-term real-field monitoring to refine predictive models for PV degradation and enhance module durability. Further detailed material analysis is ongoing to confirm intrinsic aging mechanisms and provide deeper insights into PV module reliability over time.

Keywords: *PV systems; PV module; PV degradation; PV module reliability; Fault analysis; IV characterization.*

1 INTRODUCTION: CONTEXT and AIM

Long-term monitoring of photovoltaic (PV) installations provides invaluable insights into real-world performance, degradation rates, and the underlying mechanisms that affect PV module reliability and performance over time. Earlier studies on long-term PV performance analysis in the field, examined the degradation rates of PV modules, revealing variability across different PV technologies and environmental (macro- and micro-climatic) conditions. A comprehensive review by the National Renewable Energy Laboratory (NREL) analyzed various studies and found that crystalline silicon (c-Si) PV modules exhibit degradation rates ranging from 0.4% to 0.5% per year, with system-level degradation rates being higher due to balance-of-system (BOS) components and soiling effects. Similarly, a study focusing on c-Si PV modules in Japan reported degradation rates between 0.01% and 0.47% per year, with an overall annual average of 0.27%. In contrast, other research has identified higher degradation rates under specific conditions. For instance, an analysis of monocrystalline silicon (m-Si) modules, after 20 years of field exposure, indicated a degradation rate of approximately 1.75% per year, much higher than that reported in the aforementioned studies or from that guaranteed from the manufacturers.

These variations underscore the influence of factors such as PV module design, BOM quality, installation practices, and environmental stressors on long-term PV performance. Quantifying and understanding these degradation mechanisms is crucial for improving PV module designs in terms of durability, reliability and weather resilience, as well as for accurately assessing long-term PV energy yields, considering actual PV degradation losses over time. Yet, extended datasets and systematic multiyear PV monitoring studies, particularly for diverse PV technologies and field conditions, remain relatively scarce.

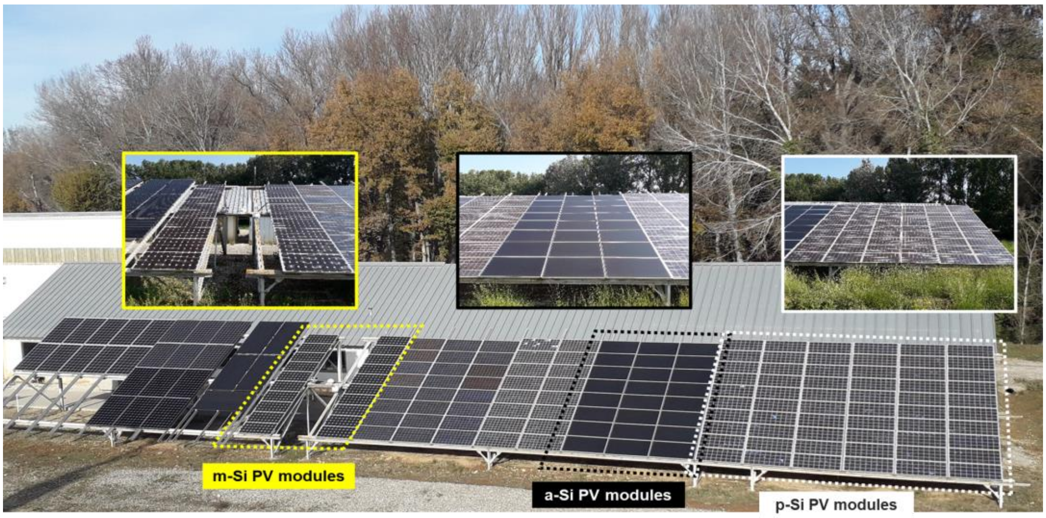

Figure 1: Overview of the studied PV test arrays installed in Cadarache site.

Since its launching in early 00's, CEA's outdoor PV test site in Cadarache has been vital resource to our research, for understanding in-field lifelong performance and aging of PV modules. The site is located in southern France, about 30km north-east of Aix-en-Provence, in a region with generally little rainfall ("hot dry-summer" climate, classified as *Csa*, per the Köppen climate classification). This research focuses on three distinct technologies (Fig. 1): polycrystalline silicon (p-Si), amorphous silicon (a-Si), and monocrystalline silicon (m-Si).

Each system, rated at 1 kWp, has been continuously monitored under identical environmental and operational conditions. These systems are paired with SMA SWR1100E inverters and complemented by an array of high-precision environmental sensors to capture irradiance, wind speed, temperature, and other key parameters. The primary objectives of this study are:

1. To quantify long-term performance degradation rates for different PV technologies under real-field conditions, for the case of Cadarache site and climate characteristics.
2. To identify and analyze mechanisms (physico-chemical, electrical, thermal, optical) responsible for module aging.
3. To bridge the gap between field performance data and laboratory findings.

2 METHODOLOGY – APPROACH

The PV systems at Cadarache have been monitored continuously since 2008, providing a wealth of long-term performance data. Electrical parameters such as DC voltage (U_{dc}), DC current (I_{dc}), AC power (P_{ac}), and inverter efficiency (η_i) are logged alongside environmental conditions, enabling a comprehensive assessment of system performance. Monitored environmental parameters include: i) *irradiance* (measured using multiple pyranometers and reference cells installed both in-plane and horizontally; ii) *temperature* (both ambient and at PV module level, using precision sensors); *wind speed* (recorded to assess cooling effects on module temperature and its impact on efficiency). Standardized performance indicators are calculated, including reference yield (Y_r), array yield (Y_a), system losses (L_s), and performance ratio (PR), providing an integrated view of energy production efficiency. To identify thermal anomalies, regular thermal imaging surveys were conducted. These images help detect potential issues such as hot spots, which could be indicative of early-life or mid/end-life faults, such as cell cracks or bypass diode failures.

To complement field measurements, selected modules were dismantled and subjected to indoor (laboratory) characterization at CEA-INES premises, to enable a deeper understanding of material degradation and failure mechanisms. The characterization methods include:

- Flash Tests (IV characterization, under standard test conditions (STC), employing a A+ PASAN solar simulator) to quantify power loss, compare against baseline measurements and identify known IV patterns related to faults (if any);
- Electroluminescence (EL) imaging, to identify potential cracks and their propagation, inactive regions, etc.;
- Visual inspections, to document physical damage such as discoloration, delamination, corrosion;
- Component-level forensics: Ongoing "autopsies" involving microscopic and material analyses of PV components.

The p-Si modules, which exhibited the highest degradation rate, were prioritized for in-depth analysis. Laboratory autopsies focus on uncovering intrinsic and extrinsic factors contributing to performance loss. Results from these analyses are compared with thermal imaging, IV curve measurements, and field data to establish correlations and identify dominant degradation pathways. This holistic methodology ensures a robust understanding of aging mechanisms.

3 RESULTS and DISCUSSION

Overall results (Fig. 2) from field-monitored data indicate significant performance degradation for p-Si modules, with an average annual degradation rate of 2%. This value is considerably higher than the 0.8% annual degradation rate specified by the manufacturer. In contrast, m-Si and a-Si modules showed lower degradation rates, with m-Si modules demonstrating better long-term stability.

Figure 2: Top: Evolution of PR for the studied modules (2010–2022). Bottom: PR decrease for the p-Si modules for the same period.).

Comparative IV curve measurements taken in 2008 and 2023 revealed substantial reductions in current output for p-Si modules (Fig. 3). Flash tests confirmed power losses ranging between -33% and -70%, suggesting both intrinsic material degradation and external environmental factors as contributors. In quantitative terms, higher losses are derived from significant drop in the P_{mpp}, fill factor (*FF*) and I_{mpp}, corresponding up to -41%, -36% and 27%

respectively, in direct correlation with a significant increase of the series resistance (R_s) by up to 2.6× times its initial value, while the shunt resistance (R_{sh}) has been decreased by up to 5.4× times from its initial value.

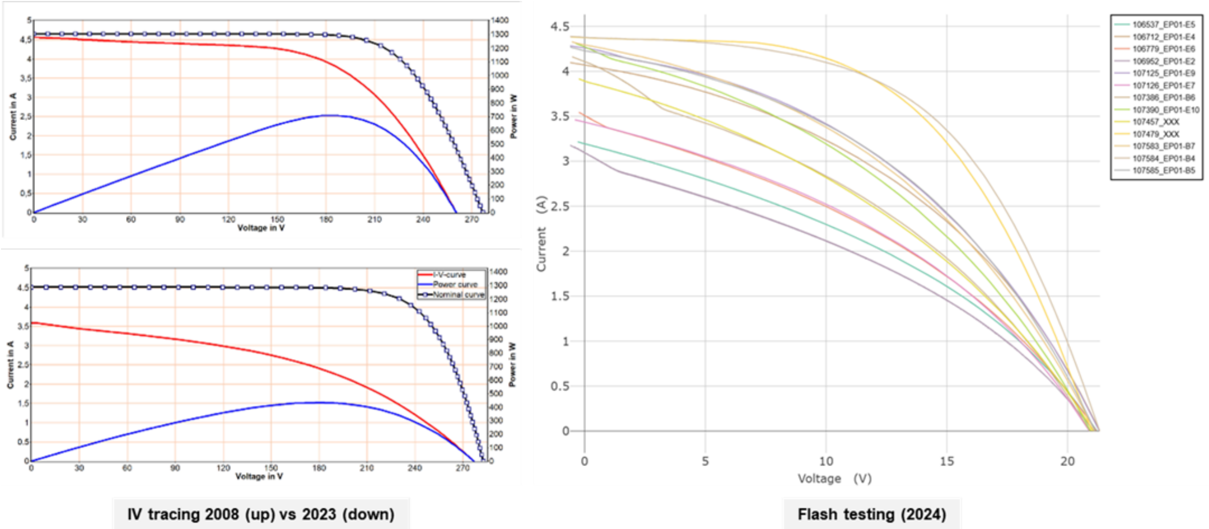

Figure 3: Left: I-V and P-V characteristics comparison (2008 vs. 2023) for the p-Si modules, through in-field IV tracing. Right: Indoor flash tests results for all p-Si modules in 2024, i.e. after 15 years completed with field exposure.

Further field inspections, via IR imaging, identified one module with a hot spot (Fig. 4), but no significant localized failures were observed in other modules. This supports the hypothesis that performance loss is generally uniform across all modules. EL analysis further revealed extensive microcracks and inactive cell regions, correlating with the observed power loss.

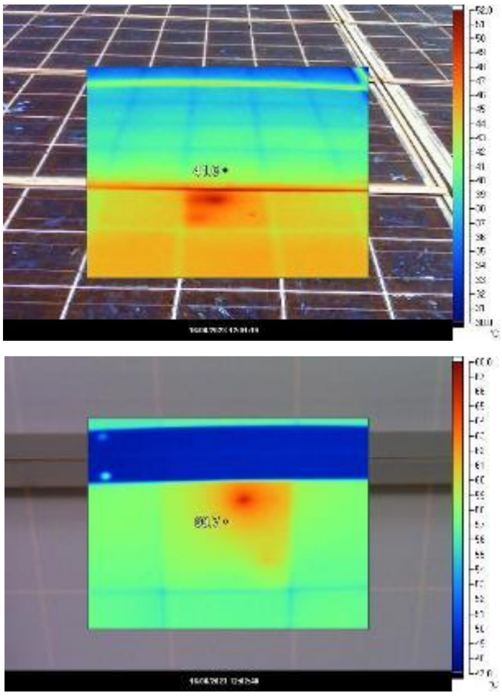

Figure 4: Examples of IR images obtained for one of the studied p-Si modules, suggestive of an occurring hot spot.

Visual inspections (Fig. 5) identified some signs of discoloration and burnt marks from localized overheating (in the case of the aforementioned hot spot) and light corrosion in the junction boxes, as well as some suspected – yet not confirmed, starting delamination. On the other hand, bypass diodes and electrical connectors were found to be in good condition, ruling out major failures in these components. None of the (suspected) cell cracks was visible by naked eye.

A detailed material analysis of the p-Si modules is underway to investigate intrinsic aging mechanisms and confirm potential faults, suspected through the IR, EL and visual inspections. Early observations suggest that the degradation is not confined to specific cells but is distributed, rather uniformly, across all modules in the array.

On the basis of these results and discussion, key takeaways (so far) can be summarized in the following:

1. **Degradation Rates**: The p-Si modules exhibited a degradation rate of 2% per year, significantly higher than warranty expectations. In contrast, m-Si and a-Si modules showed better durability under the same environmental conditions.
2. **Mechanisms of Degradation**: Laboratory analyses confirmed that power losses in p-Si modules are primarily due to uniform cell degradation, as evidenced by EL imaging and IV curve measurements. External factors such as thermal cycling, UV exposure, and material aging likely contributed to the observed trends.
3. **Thermal and Visual Observations**: Despite some visible damage (discoloration and delamination), no critical failures were found in bypass diodes or junction boxes. The uniformity of degradation suggests systemic aging mechanisms rather than isolated defects.
4. **Relevance for Industry**: The findings underscore the importance of real-world, long-term monitoring for validating manufacturer warranties and improving predictive models for PV performance.

The study, so far, sets the stage for a deeper exploration and understanding of the degradation mechanisms occurring in the studied PV modules, as they approach the end of their service life. More detailed and comparative results, including further characterization techniques, comprehensive discussion and sensitivity analysis, are ongoing and will be included in a future work.

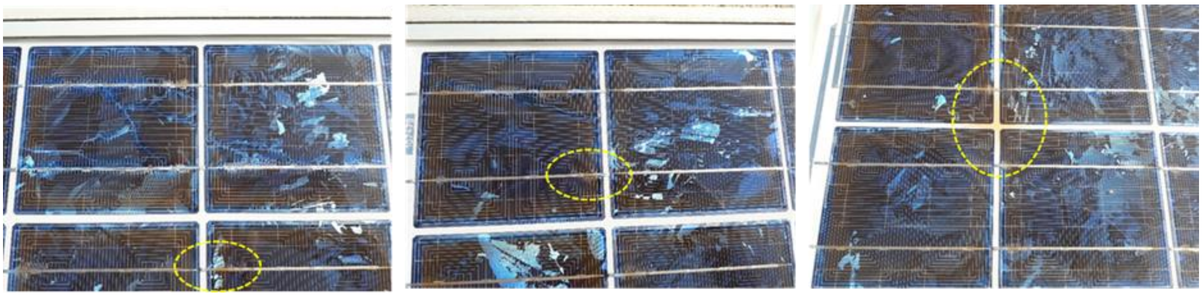

Figure 5: Examples of degradation and faults identified or suspected during visual inspection, for the case of p-Si modules.

4 CONCLUSIONS - OUTLOOK

This study provides a comprehensive 15-year performance evaluation of polycrystalline, monocrystalline, and amorphous silicon PV modules exposed to real-field conditions at CEA's Cadarache test site. Results reveal a markedly higher degradation rate for polycrystalline silicon modules (≈2%/year) compared to manufacturer warranty expectations, with cumulative power losses between -33% and -70%. Infrared and electroluminescence analyses confirmed that degradation is largely uniform across modules, dominated by microcracks, inactive cell regions, and increased resistive losses, while bypass diodes and connectors remained intact. In contrast, monocrystalline and amorphous silicon modules exhibited lower degradation rates, underlining the importance of both technology choice and bill of materials quality for long-term PV durability.

The findings demonstrate the critical value of long-term field monitoring in complementing laboratory tests and refining predictive models for PV reliability. By correlating outdoor performance data with laboratory diagnostics, this study highlights systemic degradation pathways that cannot be captured by short-term testing alone. Future work will expand on the ongoing material-level analyses to pinpoint intrinsic aging mechanisms and validate failure hypotheses.

Looking ahead, these insights can support:

- improved module design and material selection to enhance resilience against thermal cycling, UV exposure, and environmental stressors,
- more accurate degradation models for lifetime energy yield predictions, and
- updated warranty and reliability frameworks aligned with field-verified performance.

Ultimately, the results contribute to a more robust understanding of PV module lifetimes in real-world conditions, helping bridge the gap between manufacturer guarantees and field realities, and reinforcing the importance of continuous, multi-year monitoring for the sustainable deployment of PV technologies.

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