Early and Abrupt Degradation of CIGS Systems Deployed in Diverse Climatic Conditions

Summary

This work presents a mid-term performance analysis of four CIGS PV systems installed in distinct regions of Peru: the coastal desert of Lima, the tropical rainforest of Chachapoyas, the semi-arid highlands of Tacna, and the extreme high-altitude conditions of Juliaca. Significant PR losses were identified in Lima and Juliaca, with values dropping from about 0.85 to 0.69 and 0.65, respectively, after one year and just four months of operation. In Tacna, the CIGS system declined to 0.77 after 18 months and remained stable, while in Chachapoyas, the PR dropped to 0.68 after 3.5 years but recovered to 0.75 in the fourth year. Upon identifying these deviations from the expected PR, an in-depth characterization was carried out on the Lima system. I-V curves and electroluminescence (EL) were performed, allowing the identification of power loss linked to decreased FF in the STC-translated I-V curves and revealing deactivated regions. To enable quantitative EL, a tool was developed to identify areas actively contributing to power.

Keywords: CIGS degradation, electroluminescence, outdoor PV monitoring, high-altitude PV systems.

1. Introduction

Copper Indium Gallium Selenide (CIGS) PV modules have gained attention for their high efficiency, favorable temperature coefficients, and suitability for lightweight and flexible applications. Despite these advantages, their long-term reliability under real outdoor conditions remains active research, especially given the emerging evidence of degradation phenomena such as partial shading-induced shunts and potential-induced degradation effects (Yilmaz et al., 2022). Recent studies have evaluated the performance of CIGS technologies across various climatic regions, showing both promising yields and susceptibility to localized defects that impair PR over time (Barragán Sánchez-Lanuza et al., 2024). The literature highlights the need to assess degradation not only through energy yields, but also through advanced diagnostics such as EL imaging, which enables spatial localization of inactive areas and shunting paths (Silverman et al., 2017). In accordance with IEC 61724-1:2021, PR is one of the key indicators for evaluating PV systems under outdoor conditions. Furthermore, the standard IEC 60904-1-2 provides guidelines for translating I-V characteristics from outdoor to STC, while IEC 60904-13:2020 recommends methodologies for capturing and interpreting EL images for thin-film technologies such as CIGS. Understanding the degradation mechanisms and their impact on PR under diverse outdoor conditions is essential to support data-driven decisions regarding PV system operation, maintenance, and technology selection.

2. Experimental details

The CIGS PV systems, Fig. 1, were deployed across four climatically diverse sites in Peru: coastal Lima, tropical Chachapoyas, semi-arid Tacna, and the high-altitude Andes Juliaca (≈3800 m a.s.l.) under a PROCIENCIA and World Bank–funded program intended to accelerate applied PV research and technology transfer. Each site's array comprises CIGS modules mounted at a 15° north-facing tilt. The modules have power rated at 115 W at STC and a nameplate efficiency >14.3 %, see table 1. Arrays are wired as two parallel strings of seven modules in series (7 × 2). Plane-of-array irradiance is measured by an MS-80M pyranometer, and module temperature by PT100; all measurements are logged at 60 s intervals in accordance with IEC 61724-1. This high-resolution sampling enables precise calculation of reference, array, and final yields, as well as capture and system losses. It allows the evolution of the CIGS performance ratio and degradation trends to be tracked over the years.

Fig. 1: CIGS system installed in Lima, numbered for EL and I-V curve analysis; identical systems are installed at all locations.

For the detailed characterization after identifying an abrupt and unexpected drop in the PR of the modules located in Lima, according to the numbering shown in the Fig. 1, specific equipment was employed. EL images were obtained using the LumiSolarOutdoor Battery system from greateyes GmbH, equipped with a 4 Mpx camera, providing high-resolution images to identify defects in the photovoltaic modules; and the I-V curves were traced using the MP-11 I-V Curve Checker from EKO Instruments.

Tab. 1: Main characteristics of the PV system with electric parameters at STC

I_{mppt} (A)	2	**V_{mppt} (V)**	57.4	**P_{mppt} (W)**	115
I_{sc} (A)	2.21	**V_{oc} (V)**	75.5	**(series, parallel)**	(7,2)

3. Result and discussion

After one year of operation in Lima, the performance ratio PR experienced an abrupt drop from values from 0.85 to a low of around 0.55. Part of the fluctuations in Fig. 2 is attributable to seasonal module-temperature; the extended proceeding will therefore provide temperature-corrected PR values. In the following months, however, a gradual recovery was observed, with the PR rising again to approximately 0.65. In Juliaca, the PR loss occurred even earlier: just four months after commissioning, the PR fell to 0.68. Since then, the system has partially recovered and maintained a stable PR of around 0.70. By contrast, Tacna and Chachapoyas exhibited more moderate declines—to 0.77 and 0.68 respectively—followed by a partial recovery (in Chachapoyas the PR returned to 0.75).

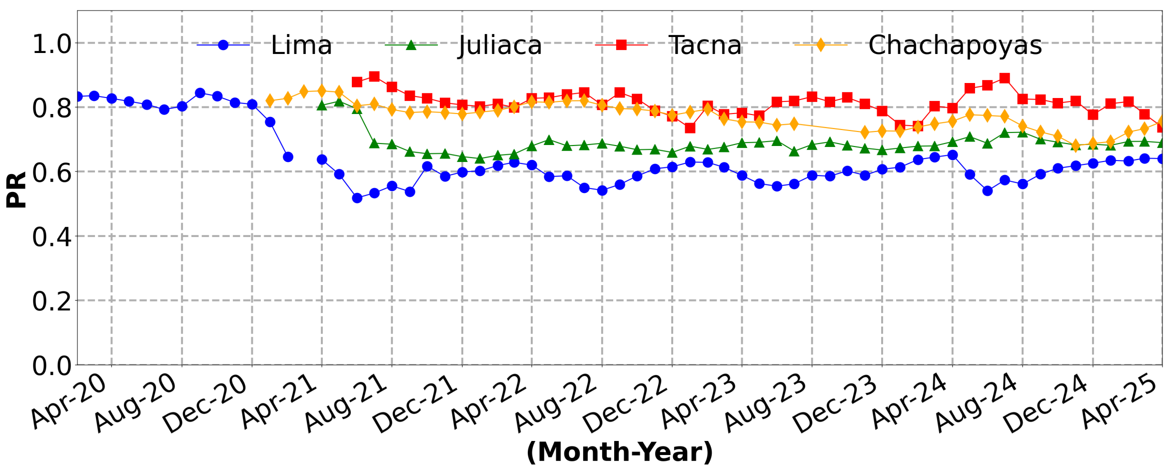

Fig. 2: PR monthly estimation for all locations, abrupt drop occurs in Lima and Juliaca.

To investigate the abrupt losses observed in Lima, diagnostics were carried out using EL imaging and I-V curve tracing. In Fig. 3, panel (a) shows a control module that was never exposed to outdoor conditions, while panel (b) displays a module from the system depicted in Fig. 1. The EL image (b) highlights regions where the module emits little or no luminescence—these dark zones correspond to areas in which electron–hole pairs recombine non-radiatively, often due to defects such as shunts. In those shunted regions, useful current flow is severely reduced or entirely absent, preventing luminescence and causing the appearance of "black" or attenuated sectors. Conversely, bright spots in an EL image typically mark locations of unusually high current concentration, often adjacent to shunt defects where carriers accumulate around the faulty region.

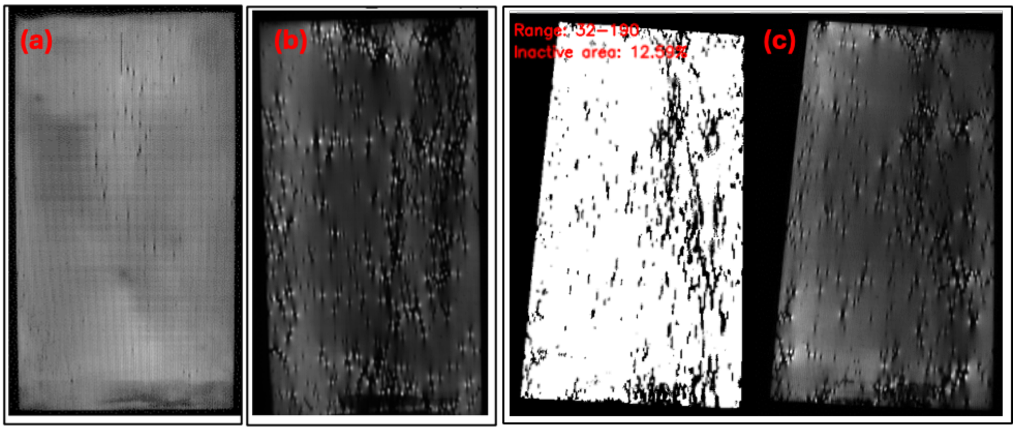

Fig. 3: (a) shows the EL image of a reference CIGS module, (b) displays the EL image of a degraded outdoor-exposed, and (c) presents the identified inactive areas, quantifying 12.59% of the module surface as non-contributing.

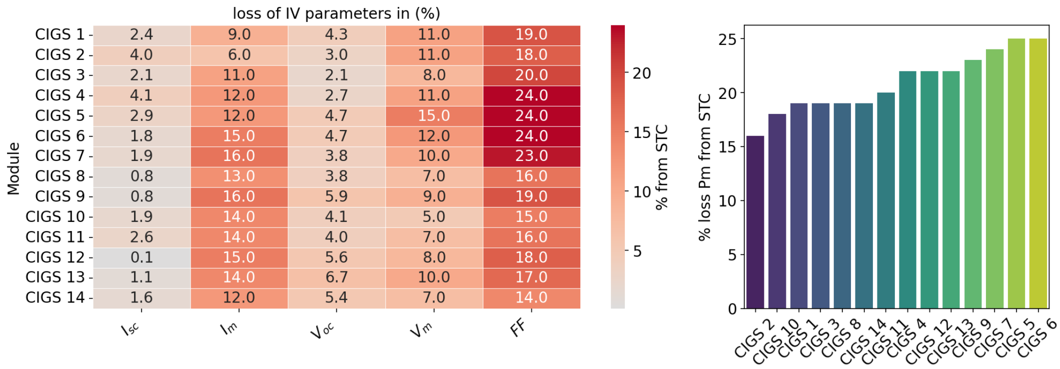

Fig. 4: Results of I-V curve translation to STC: the right panel shows percentage losses relative to the reference (Table 1), and the left panel shows STC power losses per module.

To quantify how much of the cell area remains active, a script, available in the Zenodo repository (10.5281/zenodo.15293266), was developed to identify and measure regions still contributing to power generation. For the example in panel (b), this analysis determined the inactive area to be 12.5 %. It should be noted that partially shaded cells can become reverse-biased in a series string, driving stress currents through these defective regions. Studies have shown that even brief shading events can induce irreversible damage in CIGS modules under reverse bias (Silverman et al., 2017). Fig. 4 presents the measured I-V curves alongside the losses relative to the manufacturer's STC values in Table 1. Noticeable reductions in Fill Factor (FF) reveal an increase in shunt resistance, consistent with the EL observations. The corresponding power curves indicate average energy losses of 20 %. FF losses and I_{mppt} losses are the most significant contributors to the PR decline, and the variability between modules indicates that localized defects and heterogeneous degradation are key determinants of overall CIGS system performance. Further analysis will be presented in the proceeding.

4. Reference

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