Degradation Studies of PV Technology Modules Operating in Various Applications in Minas Gerais, Brazil

Denio A. Cassini[1], Lawrence L. Kazmerski[2], Vinicius A.C. Santana[1], and Antonia Sônia A.C. Diniz

[1] Pontifical Catholic University of Minas Gerais, Belo Horizonte, MG (Brazil)

[2] RASEI, University of Colorado Boulder, Boulder, Colorado (United States)

Abstract

The viability of photovoltaic (PV) systems is directly linked to the operating performance and reliability of the PV modules. This study investigates the durability behavior of modules of different technologies under real operating conditions in several climate zones of Minas Gerais, Brazil. These include ground-based fixed and tracking power plants and floating (FPV) systems. Standard evaluations using visual inspections, thermal infrared imaging, I-V and electrical parameter characterization, and electroluminescence (EL) mapping. Trends in degradation patterns are reported for devices studied over the past 3-decades. *Pre-2005* crystalline Si experience irreversible light-induced degradation (LID) due to their p-type substrates (and associated B-O complexes). More severe were issues with encapsulant discoloration, contact corrosion, cracked cells, and delamination resulting in annual degradation rates of 4%-9%/year. Early era a-Si:H and CdTe modules exhibited critical problems with TCO decomposition with average average losses in the 3%-5%/year range. Innovation in device architectures and materials *post-2015* has resulted in higher efficiency cells and modules with general positive trends in observed reliability. However, the more rapid introduction into commercial product has led to unanticipated degradation mechanisms that have required innovation in mitigation schemes. This study reports reversible LID and possible LeTID in Al-BSF and p-type PERC modules--with elimination of this effect in n-type PERC. More concerning is shunt and polarization potential-induced degradation (PID) observed in PERC modules. Average annual degradation rates of 1.5%-5%/year are reported for ground-based (tracking and fixed) modules. However, systems exposed to *higher* irradiance, temperature, ultraviolet, and humidity conditions are shown to have *higher* losses. This is especially determined for the research floating PV (FPV) experiencing significant PID-shunt. In contast, more recent thin-film CdTe and bifacial n-type modules on this same platform exhibit negligible losses over a 2-year period.

Keywords: PV degradation, durability, reliability, PV modules, systems, solar cell technologies

1. Introduction

Brazil is now established as an important photovoltaic (PV) world markety, with cumulative capacity expected to exceed 70 GW in 2024 (Neves, 2025, Mints, 2024). With this growth, issues related to durability, reliability, and performance of photovoltaic systems have become central to the technical and economic sustainability of the sector. The State of Minas Gerais (MG) is a leading site for PV plant deployment because of its excellent annual solar resource and favorable, available terrain. Though the recent (2017-present) in PV system growth has dominated, a significant number of PV installations were implemented in the 1990-2010 timeframe. This has provided an opporunity to compare the operation and reliability of the more vintage PV technology with the higher-performance recent cell and module architectures. With the more severe local tropical/subtropical climate conditions (humidity, temperature, and elevated solar irradiance), the identification and possibly mitigation of device degradation mechanisms with the technology evolution are the focus of this study. Working with the system developers and operators to provide them this feedback is a major portion of this R&D to ensure the best-possible PV system outputs, enhancing both financial benefits and consumer confidence in solar electricity.

10.18086/swc.2025.03.17 Available at http://proceedings.ises.org

For PV devices prior to 2005, Jordan and Kurtz (2018) reported the primary degradation modes and their effects on the performance of a crystalline silicon and thin-film photovoltaic modules. The results indicated an average degradation rate of 0.7%/year for crystalline silicon, and a corresponding 1.5%/year for thin-film technologies. The prevalent degradation mode for crystalline-Si was discoloration (decomposition) of the encapsulant (EVA) (de Oliveira, 2018), and for thin-film modules, the increase in resistivity and delamination of the transparent conducting oxide (TCO). This study has observed these issues, which are enhanced by the environmental conditions in MG. Additionally, light-induced degradation (LID) is reported in this study for both p-type multicrystalline and monocrystalline Si modules. This occurs upon exposure to the sun and is usually in the 1%-4% power loss range. Of course, this degradation mode has been well investigated (Yeo.et al., 2022, Nakayashiki, et al., 2016) and is primary due to B-O complex activation, though Fe-B pair dissociation and Cu-preciptiate formation have also been identified as root causes. The result is a degradation of the minority carrier lifetime. Over longer exposure periods (100s of hours), light and elevated temperature induced degradation (LeTID) (Kersten, et al. 2015) can decrease power outputs in multicrystalline Si panels up to 20%, again at higher operating temperatures above 65 °C experienced in most sites in MG.

With device innovation after 2015, device performances have advanced--with efficiencies beyond 25% for cells. These cells have more complex structures, new materials, multiple interfaces, and thinner layers. Also, the time from laboratory demonstration to commercial introduction has decreased in this period. This has resulted in the appearance of new and unanticipated degradation mechanism that have challenged the reliability community to address these with innovative science and engineering approaches and to develop mitigation schemes. The introduction of the passivated emitter and rear contact (PERC) technology is an example--and is currently the widely adoped device in the Brazil markets. The p-type PERC modules still experience LID, but this has been mostly eliminated with the trend to n-type Si. However, with 2-3 months exposures under conditions of high humidity and temperatures and with the current high-system voltages give rise to potential induced degradation (PID). The most common type results from Na+ migration from the glass to the passivation layers causing shunts and power losses up to 40%. This is PID-shunt (or PID-s) (Kempe, 2023, Koester, et al., 2022, Puranik and Gupta, 2021). The effects are noticed in loss of power (due to decrease in R_{sh}) in cells near the frame or the negative end of the string. The use of transformerless inverters can exacerbatethe problem (Zhang, et al., 2023). Other PID modes (i.e., corrosion and polarization) can also occur (Kempe, 2023, Puranik and Gupta, 2021, Zhang, et al., 2023).

This paper presents results of a case study investigating vintage (prior to 2005) and recent (post 2015) PV technologies installed and operated in the tropical and subtropical conditions in Minas Gerais, Brazil. The reliability and degradation mechanisms are discussed and reported--covering observed material issues, LID, and PID. The effects are covered for ground mounted and floating PV systems, linking climate impacts with performance losses.

2. Materials and Methods

This report covers modules commissioned in the timeframe 1995-2005 and installed in the tropical regions of northern and northwestern regions of Minas Gerais. Typically, these were part of small systems (<10 kW) for rural electrifcation. Among these were modules from the field and reference modules (separated and stored in the dark) were avaliable for controlled laboratory testing. Systems with technologies manufacured and installed since 2015 represent the common climate conditions for ground-mounted and floating installations in these areas (e.g., Lontra, tracking; Corinto, fixed; and Grão Mogol, FPV).

All tests and measurement were conducted under IEC and ABNT standards (IEC 2025a. IEC 2025b, IEC 2025c, IEC 2025d, ABNT, 2024):

Light-Induced Degradation: For laboratory-possible light-related performance losses, PV reference modules (stored in dark) were randomly selected from the particular site's reserve. IV characteristics and thermographic imaging were the main investigation tools. For panels in existing field operation, the IR tests were performed using thermographic cameras attached to unmanned aerial vehicles (UAVs, drones). Two factors must be known to evaluate the results: the LID value and the exposure/operation time of the photovoltaic modules in the field. To assess degradation over time, electricity production monitored using dedicated *software* for PV plants, which made it possible to compare the energy generated over different periods, adjusting the data to consider climate variations, soiling levels, irradiance levels, spectral content, etc.

Visual Inspections: The visual inspections (Wohlgemuth and Kurtz, 2011) were especially important for the early-vintage modules that exhibited discolorations (e.g., encapsulant chemical changes), delaminations, back-sheet powdering, and contact corrosions.

Degradation studies: The degradation science and engineering approach for module/system evaluation followed the process: (1) Drone IR-thermographic inspection to record the temperature differences of cells within the modules (IEC 62446-3 standars). Special attention was focused on "hot spots" near the negative edge of strings and near the frame edges of the modules. The patterns provide initial insight to possible degradation causes. (2) On suspected modules from the IR mapping, IV characterization followed to acertain voltage and current levels (e.g., P_m loss), significant lowering of module R_{sh} and increased R_s. And (3) Electroluminescence (EL) mapping of the modules to detemine from corresponding cell losses (darker images indicating less light emission) for cells near the negative edges of the panel. The focus was on PID-s because it is the most common of the PID degradation modes reported.

3. Results and Discussion

Early Modules/Systems: The visual inspectionss of the mono-Si and multi-Si modules exhibited the main degradation mechanisms associated with the photodagradation of the organic encapsulation (EVA), as shown in Table 1 and Fig. 1. Figure 1a shows a mono-Si module completely degraded, with observed high delamination of the EVA. Figure 1b illustrates discoloration of the EVA (browning) as the dominant degradation mode, with associated loss of power.

The field analysis revealed distinct modes of degradation associated with the environmental and operational conditions as a function of technologies of solar cells. From visual inspection mono-Si and multi-Si PV modules manufactured up to 2005 exhibted as a main degradation mechanisms the photodegradation of the encapsulation polimeric materials, as can be seen in Fig. 1 and Table 1 the degradation rates of PV modules.

These are modules manufactured and installed *pre-2005*. Table 1 shows the degradation rates of analysed PV modules. The results indicated an average degradation rate of 7.71%/year for mono-Si and 2.41%/year for multicrystalline-Si PV modules. For thin-film technology, degradation rates of 4.53%/year for CdTe and 5.49%/year for a-Si:H. Note that these are earlier CdTe modules, and recent one (110 Wp) have degradation rates less then 0.5%/year. The majority of PV modules manufactured after 2021 had average degradation rates superior to 1.0%/year for 20 years, as warrantied by the manufacturers.

Table 1. Summary of properties and performance of early PV modules installed or manufactured before 2005.

Module Technology		**Rated Power** (Wp)	**Time in Operation** (Years)	**Degradation Rate** (%/Year)	**Average Degradation Rate *(all modules)*** (%/Year)
Silicon	Mono-Si (Al-BSF)	55	7	5.93	7.71
		55	7	9.54	
		55	7	7.65	
	Multi-Si (Al-BSF)	70	12	3.13	2.41
		50	4	3.34	
		50	14	0.77	
Thin Films	CdTe	110	6	1.55	4.53
		32	5	7.52	
	a-Si:H	64	16	0.18	5.49
		32	7	9.22	
		22	7	7.07	

Figure 1(a) shows a mono-Si PV module completelly failed, mainly caused by excessive dilamination of the EVA encapsulant. Figure 1(b) presents for multi-Si browing as dominating degradation mode. And Figure 1(c) shows the degradation mode of CdTe thin film, and its I-V curve. Figure 1c presents data from one early (approx. 1992) thin film CdTe module, with the SnO_2 TCO coating degraded due to water vapor penetration, due to the location's very high humidity, rain, and higher operating temperatures. Included in Table 1 is data from a more recent thin-film CdTe product (110-Wp) which has a superior TCO (ZnO) and superior encapsulation resulting in significantly less loss.

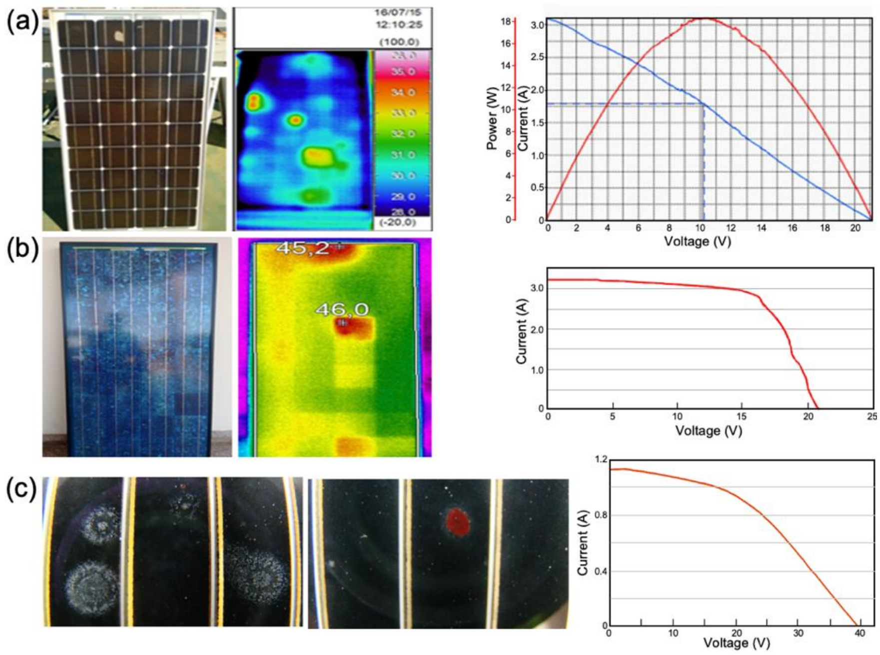

Figure 1. Early PV modules: (a) Monocrystalline Si, Al-BSF showing delaminatin of EVA; (b) Multicrystalline Si, Al-BSF showing discoloration of EVA encapsulant; (c) Early era thin-film CdTe with TCO degradation.

Table 2. Summary of recent (post 2015) power plant information, indicating operating characteistics and losses. Köppen-Geiger climate classifications are specified Köppen and Geiger, 1928).

Power Plant & Type	**Climate Classification** *(Köppen-Geiger)*	**Start of Operation** (Year)	**Cell Type**	**Power** (Wp)	**LID Power** (Wp)	**Operating Power** (Wp)	**Degradation Rate (DR)** (%/Year)	**R_S** (Ohm)	**R_{sh}** (Ohm)
Grão Mogol FPV	Subtropical (Humid: Dry winter, Wet Summer) *Cwa*	2022/ 2023	Mono p-type PERC	400	379	353	6.86	*0.32** 0.98	*800** 129.8
Crist-alina FPV	Tropical (Dry Summer) *Aw*	2017	Multi p-type Al-BSF	265	257	228	1.88	*0.30** 0.74	*350** 50.4
Lontra Fixed	Tropical (Dry Summer) *As*	2019/ 2020	Mono p-type PERC	430	406	385	1.29	*0.28** 1.27	*1200** 472.8
Corinto Tracking	Tropical (Dry Winter) *Aw*	2019	Multi p-type Al-BSF	330	318	300	1.19	*0.32** 0.82	*400** 135.7

*reference data from manufacturers

<u>Recent Modules/Systems</u>: Table 2 shows the results of LID and degradation rate for PV modules manufacturers after 2015, installed in distinct climate zones. The ground FPV plants with tracking (Lontra) and fixed (Corinto), the annual degradation rates (DR) were for p-type PERC (mono-Si) slightly above 1%/year and for the FPV Cristalina with multi-Si modules <2%/year. (Note: Cristalina is adjacent to the western border of MG in Goás State, but it was included as a site in this case study. It is also the 1st FPV plant in Brazil, installed in a rainwater collection site for agricutural irrigation.) Initial stages of PID-s are suspect for these installations based on the losses in R_{sh}.

The DR for monocrystalline-Si p-type PERC in the FPV Grão Mogol were very high for 1-year+ operation, reaching 6.9%/year. The most likely mechanism is PID-s due to the presence of high UV and visible solar irradiation, high temperatures, very high humidity and resulting leakage currents. PID shunt causes a gradual degradation of module efficiency over time, usually within weeks or months after installation, at the presence of constant humidity that can penetrate the interior of the photovoltaic module through sealing failures or via the back film of the photovoltaic module. The presence of moisture inside the module will compromise the encapsulant, which will release acetic acid that will initiate the corrosion of the cell's metal grid. It also significantly decreases R_{sh} and increases R_S. Figure 2 shows the pattern of the IR imaging, correlated with reportedd PID shunt (Cassini, 2025).

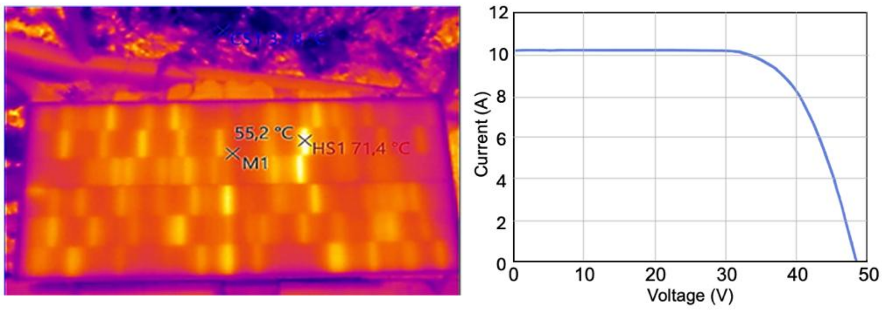

Figure 2. Thermographic image of post 2015 module (p-PERC) indicating PID-shunt degradation.

4. Summary and Conclusions

The definite improvement in PV module performance from early era (***before 2005***) to recent (***post 2015***) has been demonstrated through these case studies. For PV modules manufactured before 2005, the average annual rates of degradation were higher for mono-Si (7.71%/year) than for multi-Si (2.41%/year), and the main degradation modes were browning and delamination of the encapsulation (EVA) and some contact corrosion. For thin film technologies, CdTe thin film has lower rates (4.54%) than a-Si:H (5.49%/year, both having issues with the TCO. For PV modules manufacturers after 2015 (for ground-mounted systems), the degradation rates were for p-PERC 1.29%/year and multi-Si 1.19% and the DPR for FPV were for mono PERC-type p 6.86%/year and multi-Si 1.88%. The main mechanisms found were PID (polarization) and possible PID-shunt for PERC photovoltaic module due to high temperature and humidity. This case study contributes to increase the understanding of the factors that affect the durability of PV modules in Brazil's climate zone. The results have been shared with the developers/operators of the site resulting in understanding and some mitigation of the problems.

5. Acknowledgments

The authors would like to thank the collaborators of the GREEN Laboratory (Energy Study Group), the Graduate Program in Mechanical Engineering of the Pontifical Catholic University of Minas Gerais, and especially CEMIG for their support and collaboration on this project. This work was carried out with the support of CNPq, CAPES (Brasil), FAPEMIG, CEMIG, & the Fulbright Scholar Program.

6. References

ABNT, Brazilian Association of Technical Standards, 2024. ABNT NBR IEC 61215-1:2024, Ground PV modules. https://abnt.org.br/noticia/2980/Módulos-fotovoltaicos-terrestres-(FV)-—-Qualificação-de-projeto-e-aprovação-de-tipo.-Parte-1:-Requisitos-de-ensaio

Cassini, Dênio Alves. **Estudo da qualidade, durabilidade e confiabilidade de módulos fotovoltaicos em diferentes zonas climáticas**. 2025. 165 f. Tese (Doutorado) - Pontifícia Universidade Católica de Minas Gerais. Programa de Pós-Graduação em Engenharia Mecânica. Disponível em: https://bib.pucminas.br/teses/EngenhariaMecanica_DenioAlvesCassini_31659_TextoComplet o.pdf. Call number: 620.91(815.1) C345e TP de Oliveira, Michele Cândida Carvalho, Diniz, Antonia Sônia Alves Cardoso, Marcelo Machado Viana, Marcelo Machado, Cunha Lins, Vanessa de Freitas, 2018. The causes and effects of degradation of encapsulant ethylene vinyl acetatecopolymer (EVA) in crystalline silicon photovoltaic modules: A review. Renewable and Sustainable Energy Reviews 81, 2299-2317. https://doi.org/10.1016/j.rser.2017.06.039

IEC 2025a, Technical Specificaion 61215-1. Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1: Test requirements/ https://webstore.iec.ch/en/publication/61345

IEC 2025b, Technical Specification 62804-1. Photovoltaic (PV) modules - Test methods for the detection of potential-induced degradation - Part 2: Crystalline silicon. https://webstore.iec.ch/en/publication/71747

IEC 2025c, Technical Specification 62804-2. Photovoltaic (PV) modules - Test methods for the detection of potential-induced degradation - Part 2: Thin-film. https://webstore.iec.ch/en/publication/33260

IEC 2025d, Technical Specification, - 61646:2008. Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval. https://webstore.iec.ch/en/publication/5697

Jordan, D.C., Kurtz, S., 2018. Photovoltaic degradation rates - An analytical review. Progress in Photovoltaics: Research and Applications 21, 12-19. https://doi.org/10.1002/pip.1182

Kempe, M., 2023. Experimental considerations for estimating degradation in PV modules, Tutorial at IEEE PVSC, San Juan, Puerto Rico, 2023. Available NREL Report: https://docs.nrel.gov/docs/fy24osti/86620.pdf

Kersten, Friederike, Engelhart, Peter, Ploigt, Hans-Christoph, et al., 2015. Degradation of multicrystalline silicon solar cells and modules after illumination at elevated temperature. Solar Energy Materials and Solar Cells 142, 83-86. https://doi.org/10.1016/j.solmat.2015.06.015

Koester, L., Lindig, S., Louwen, A., Astigarraga, A., Manzolini, G., Moser, D., 2022. Review of photovoltaic module degradation, field inspection techniques and techno-economic assessment. Renewable and Sustainable Energy Reviews 165, 112616. https://doi.org/10.1016/j.rser.2022.112616

Köppen, W, Geiger, R., 1928. Klimakarte der erde (published map). Justus Perthes, Gotha.

Mints, P. (2024, 2025). The Solar Flare, SPV Market Research, Issues 1-5, 2025 and Issues 1-4. 2025.

Nakayashiki, K., Hofstetter, J., Morishige, A.E., *et al*., 2016. Engineering solutions and root-cause analysis for light-induced degradation in p-type multicrystalline silicon PERC modules, IEEE Journal of Photovoltaics 6, no. 4, 860-868. doi: 10.1109/JPHOTOV.2016.2556981

Neves, Lívia, 2025. Solar to add 13 GW in Brazil in 2025 amid signs of slowdown. PV Magazine, August 28, 2025. https://www.pv-magazine.com/2025/08/28/solar-to-add-13-gw-in-brazil-in-2025-amid-signs-of-slowdown/ ; See also, ABSOLAR, “Energia Solar Fotovoltaica no Brasil,” No. 74, December 10, 2024. Available through the link: https://www.absolar.org.br/mercado/infografico/

Puranik, V.E., Gupta, R., 2021. Spatial investigation and analysis of PID shunting in crystalline silicon PV module, 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), Fort Lauderdale, FL, USA, pp. 2372-2375. doi: 10.1109/PVSC43889.2021.9519012

Wohlgemuth, J.H., Kurtz, S., 2011. Reliability testing beyond qualification as a key component in photovoltaics progress toward grid parity. Proceedings of the IEEE International Reliability Physics Symposium, Monterey, 5E. 3.1–5E, 2011. doi: 10.1109/IRPS.2011.5784534

Yeo, Z.Y., Ling, Z.P., Ho, J.W., Lim, Q.X., So, Y.H., Wang, S., 2022. Status review and future perspectives on mitigating light-induced degradation on silicon-based solar cells/ Renewable and Sustainable Energy Reviews 159, 112223. https://doi.org/10.1016/j.rser.2022.112223

Zhang, Wenping, Wang, Yiming, Xu, Po. Li, Donghui, Liu, Baosong, 2023. A potential induced degradation suppression method for photovoltaic systems. Energy Reports 10, 3955-3969. https://doi.org/10.1016/j.egyr.2023.10.064