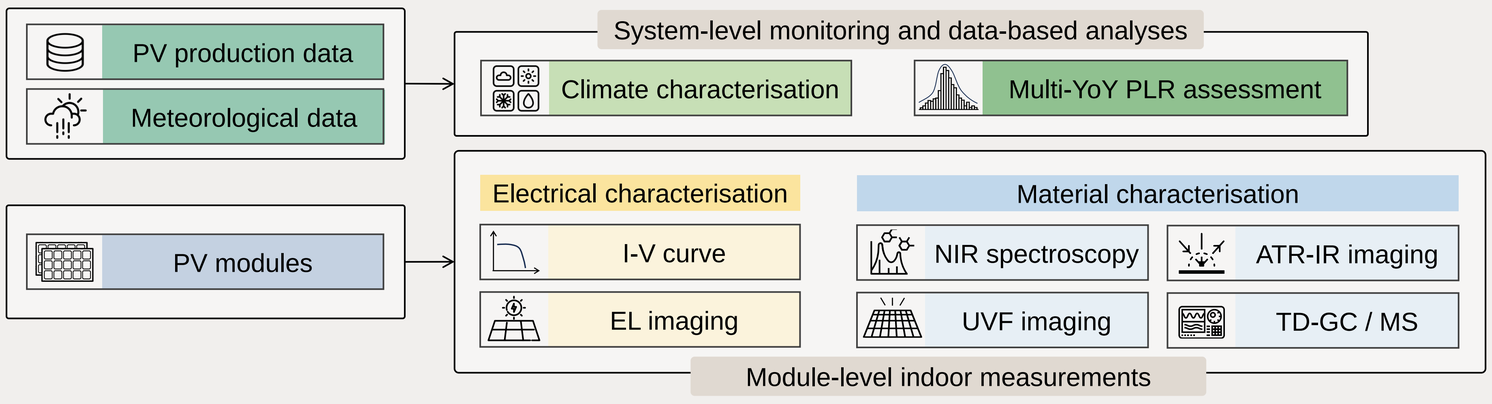
Three decades, three climates: Insights and lessons on PV reliability

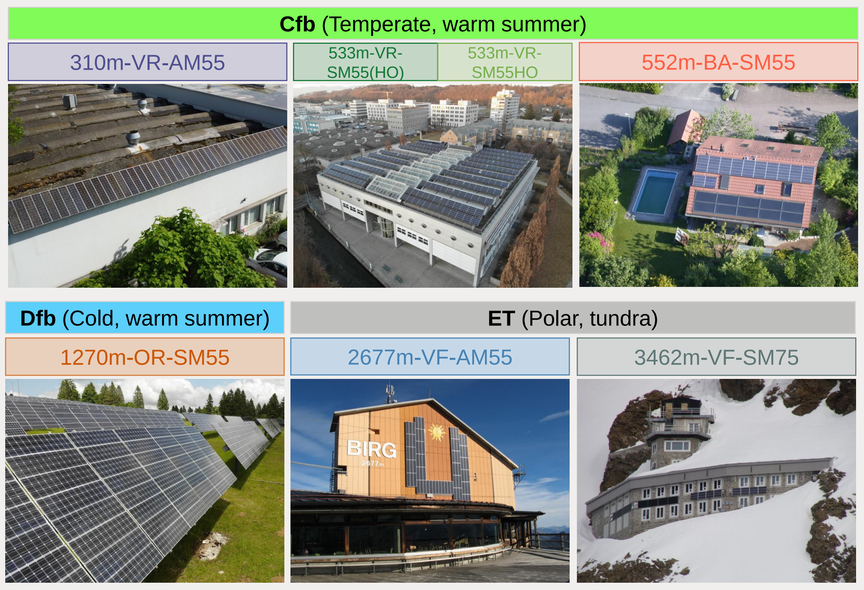
Hugo Quest[1,2*], Ebrar Özkalay[3], Anika Gassner[4,5], Alessandro Virtuani[6,7], Gabriele C. Eder[4], Stefanie Vorstoffel[8], Claudia Buerhop-Lutz[8], Gabi Friesen[3], Christophe Ballif[1,6], Matthias Burri[9], Christof Bucher[9]

1 – EPFL, Neuchâtel, 2002, Switzerland, 2 – 3S Swiss Solar Solutions AG, 3645, Switzerland, 3 – SUPSI, Mendrisio, 6850, Switzerland, 4 – OFI, Vienna, 1030, Austria, 5 – Vienna University of Technology, Vienna, Austria, 6 – CSEM, Neuchâtel, 2002, Switzerland, 7 – Officina del Sole srl, Milan, 20145, Italy, 8 – HI ERN, Erlangen, 91058, Germany, 9 – BFH, Burgdorf, 3400, Switzerland

Context and Methods

Analysis of the long-term performance of six PV systems in Switzerland over three decades and three distinct climates.



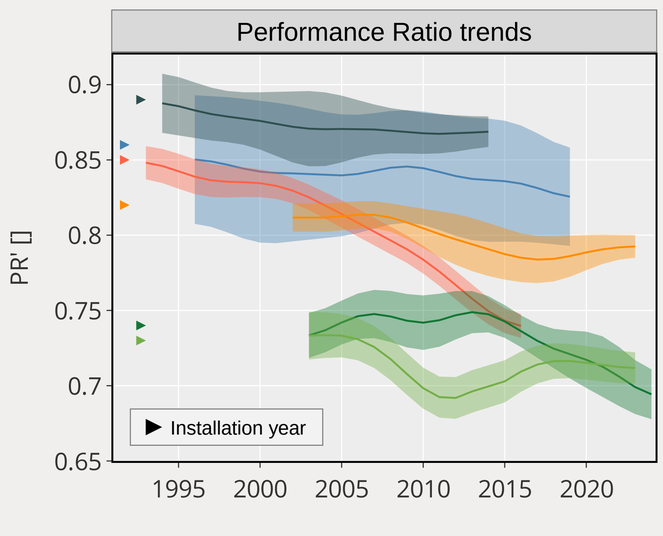


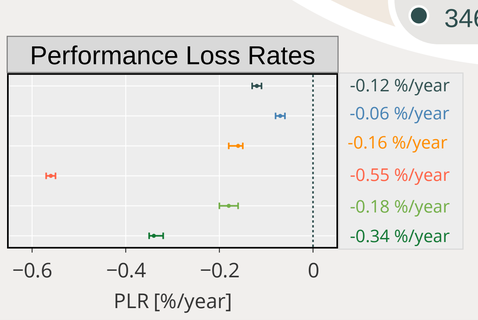
System-level monitoring

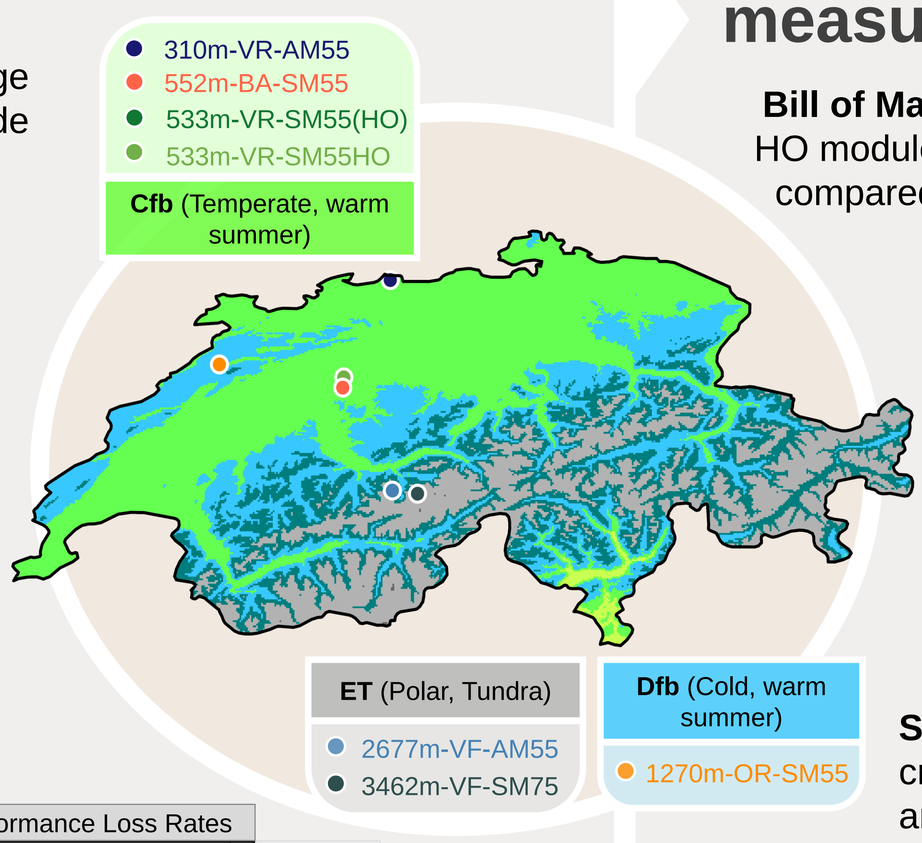
Higher altitude systems show higher average PR' (0.7 to 0.89), especially for the alpine facade at 3462m.

Facade-mounted systems exhibit higher seasonal performance variations (wider standard deviation).

Non-linearities in low-altitude systems are linked to soiling/cleaning events and possibly non-linear degradation.



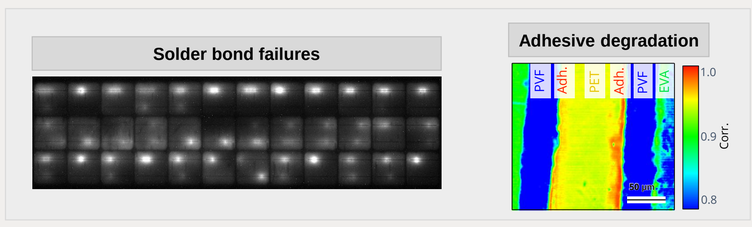




Module-level indoor measurements

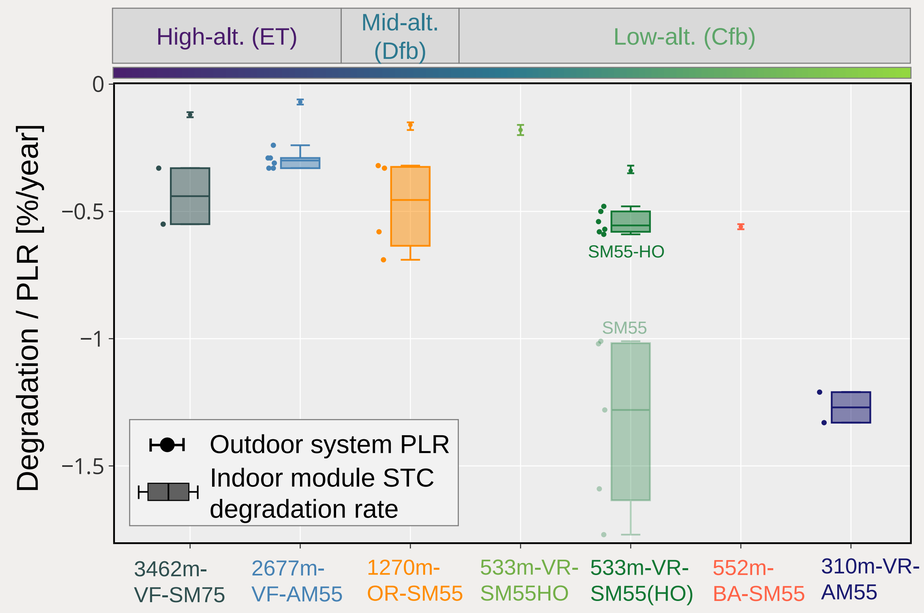
Bill of Materials (BOM): Despite identical labels, SM55-HO modules had modified backsheets (with $CaCO_3$ filler) compared to SM55, leading to lower degradation due to improved material composition.

Altitude impact: Modules at higher altitudes showed less encapsulant degradation and acetic acid formation due to cooler operating temperatures, leading to improved stability.



Solder bond failures: Recurring solder bond cracking caused increased series resistance and fill factor loss in SM55/AM55 modules, highlighting manufacturing quality issues.

Material degradation: Localised dark areas in EL images corresponded to higher acetic acid levels and adhesive breakdown, particularly in lower altitude, hotter sites.



Overview of indoor and outdoor results: (i) module P_{mp} degradation rates from indoor I-V measurements; (ii) system PLR from outdoor monitoring.

Conclusion

- **Reliability:** 1980s-1990s modules show excellent durability, with PLRs averaging -0.24±0.16%/year, well below typical rates.
- **Altitude Effect:** High-altitude sites (20°C cooler) show lower PLRs and less material degradation than low-altitude sites.
- **Material Degradation:** Low-altitude systems face more encapsulant degradation (acetic acid formation), causing corrosion and performance loss.
- **BOM Priority:** BOM is key to long-term PV reliability, and altitude has a secondary but positive influence.

Acknowledgements

ASSURed PV

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

References

[1] Ascencio-Vásquez et al. (2019), Methodology of Köppen-Geiger-Photovoltaic climate classification and implications to worldwide mapping of PV system performance, doi: 10.1016/j.solener.2019.08.072.
[2] Quest et al. (2023), doi: 10.1002/pip.3762
[3] Özkalay et al. (2022), doi: 10.1109/JPHOTOV.2021.3114988
[4] Quest et al. (2024), doi: 10.1002/pip.3855
[5] El Boujdaini et al. (2022), 'Analysis of non-linear long-term degradation of PV systems', WCPEC-8

PV Tagung 2025 (1st – 2nd April)

* hugo.quest@epfl.ch
hugo.quest@3s-solar.swiss