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Quantifying Performance Loss Rates of Photovoltaic Modules Using Ground-based vs Satellite-based Meteorological Data

E. Özkalay[1,2], A. Virtuani[2], A. Fairbrother[2] , A. Skoczek[3], G. Friesen[1], M. Caccivio[1], C. Ballif[2,4]

[1] Insitute of Applied Sustainability to the Built Environment, SUPSI, Via Flora Ruchat-Roncati 15, 6850 Mendrisio, Switzerland

[2] École Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Photovoltaics and Thin Film Electronics Laboratory (PVLAB), Rue de la Maladière 71b, 2000 Neuchâtel, Switzerland

[3] Solargis s.r.o., Mytna 48, 811 07 Bratislava, Slovakia

[4] CSEM PV-Center, Rue de Jaquet-Droz, 2002 Neuchâtel, Switzerland

ABSTRACT

Accurate assessment of the long-term performance of photovoltaic (PV) systems is critical for manufacturers, investors, plant owners and O&M companies. Many PV systems, especially residential and some commercial/industrial systems, are not equipped with meteorological monitoring systems such as irradiance and temperature sensors. Whereas to calculate the performance ratio (PR), a common performance measure, the plane of array irradiance (G_{POA}) is an input parameter. The irradiance data is the largest contribution to uncertainty in PR. Therefore, in this study, we first evaluate satellite-based irradiance and compare to ground-based irradiance data. Next, we investigate the accuracy of using the satellite-based meteorological data in long-term performance analysis of three test modules in the absence of ground-based data. We use (1) ground-based and (2) satellite-based data separately as input irradiance. We calculate 60 PR time series and performance loss rates (PLR) for each irradiance data using different filtering methods and performance metrics. As a representative PLR value, we used the mean value (excluding outliers) of the various PLR values obtained as suggested by IEA PVPS Task 13. For the first module, this method gave almost identical PLR values (-0.5% error) when ground- and satellite-based data are used. For the other two modules, the values are not identical, but standard deviations largely overlap. We show that when the mean of PLR values is used, it is possible to accurately evaluate the long-term performance using satellite-based meteorological data.

Method

- Table I provides a definition of the ground-based and satellite-based meteorological monitoring systems that have been used in this work. **Ground G_{POA}** (20˚tilt and -4˚ azimuth from South) and **module temperatures** were monitored every minute between December 2015 and May 2019 by well-calibrated (and maintained) **thermopile pyranometer** and **Pt100** sensors, respectively, on the outdoor test site of SUPSI, in Canobbio (Switzerland, 46.02°N and 8.91°E).
- The **PLR of three crystalline silicon (c-Si) PV modules** were calculated. The DC yields were monitored for almost four years between December 2015 and May 2019 at SUPSI, in Canobbio, Switzerland. The electrical performance parameters of the modules were acquired using maximum power point (MPP) trackers at 1-minute intervals.
- Not a single PLR analysis method was applied, but various PLR analysis methods applied to each long-term performance of PV modules as suggested by IEA PVPS Task 13. Each PLR analysis method is a combination of **data filtering method**, **performance metric** and **statistical analysis tool**. We created **60 PLR analysis methods** using **30 different data filtering methods, 2 different performance metrics** and **1 statistical tool (Figure 1)**. The 30 data filtering methods were created using different combinations of **irradiance**, **power**, **instantaneous PR**, **power-irradiance relation** and **clear-sky** filters **(Table II)**.

Table I. Definition of ground-based and satellite-based input meteorological data.

	Ground-based Monitoring System	Satellite-based Monitoring System
G_{POA}	On-site pyranometer (properly maintained and calibrated)	Satellite-derived
Module Temperature	Temperature sensor - Pt100 (back of module) (properly maintained and calibrated)	Calculated from satellite-derived ambient temperature using Ross' approximation

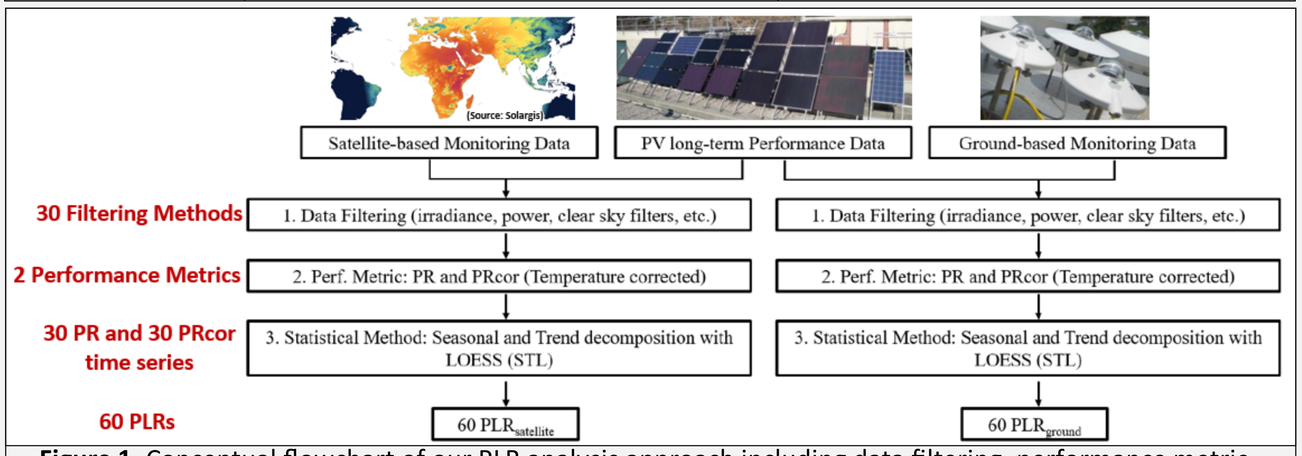


Figure 1. Conceptual flowchart of our PLR analysis approach including data filtering, performance metric computation and statistical method steps.

Results

- Figure 2a shows monthly **normalized bias series of satellite-derived G_{POA} ($G_{POA,satellite}$)**. The monthly $G_{POA,satellite}$ is **overestimated in summers** and **underestimated in winters.** As expected, this bias has an effect on **monthly $PR_{satellite}$(Figure 2b)**.

Figure 2a. Time-series of normalized bias for monthly satellite-derived G_{POA} with respect to ground-measured insolation. **b.** Time-series of monthly PR computed using ground- and satellite-based insolation.

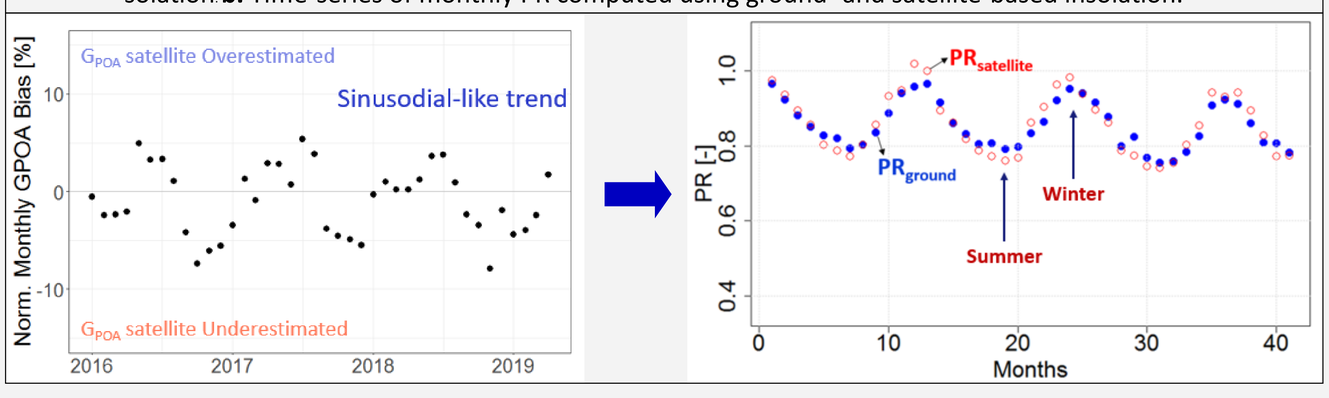


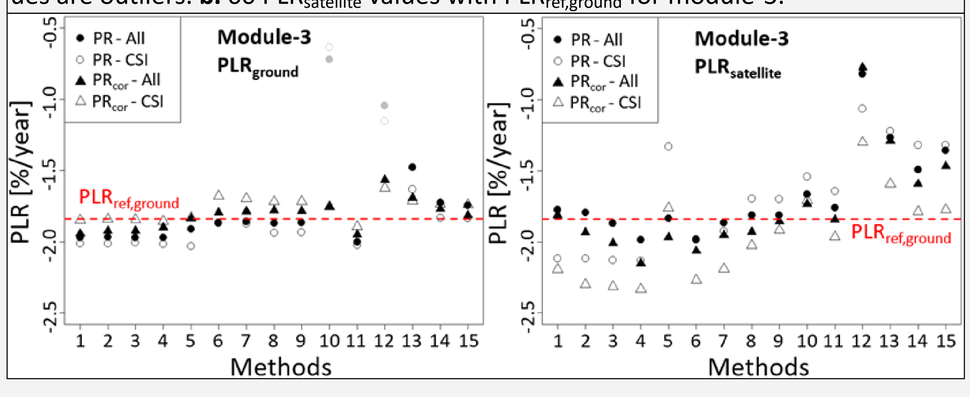
Table II. Summary of the data filtering techniques used. The parameters changed are written in bold.

Filter-1: Irradiance Threshold	**Filter-2: Clear Sky**
50 W/m² < G_{POA} < 1250 W/m² **100** W/m² < G_{POA} < 1250 W/m² **200** W/m² < G_{POA} < 1250 W/m² **500** W/m² < G_{POA} < 1250 W/m²	RdTools' CSI (Clear sky index)
Filter-3: Power Threshold	**Filter-4: Power - Irradiance**
0.01 x P_{nom} < P_{meas} < **1.2** x P_{nom} 0.01 x P_{nom} < P_{meas} < **1.02** x P_{nom}	LQ: **20th**, UQ: **80th** LQ: **10th**, UQ: **90th** LQ: **5th**, UQ: **95th**
Filter-5: Instantaneous PR (5-minute)	
±1σ **±2σ** **0.3** < PR_{ins} < **1.2**	

G_{POA}: Plane of array irradiance, **P_{nom}:** Nominal power, **P_{meas}:** measured power, **PR_{ins}:** instantaneous PR, **LQ:** Lower quantile, and **UQ:** Upper quantile.

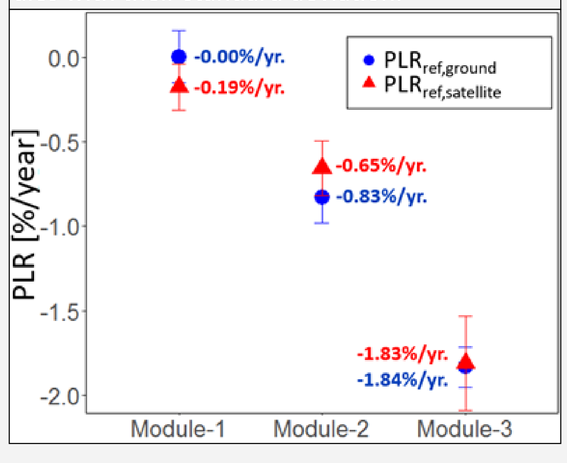
- **Figure 3a and 3b** show the **60 PLR_{ground}** and **60 $PLR_{satellite}$** values, respectively, with the $PLR_{ref,ground}$ for the same module. $PLR_{ref,ground}$ is the refenrence value which is the mean of the different PLR_{ground} values as suggested by IEA PVPS Task 13. The $PLR_{satellite}$ values are more scattered than the PLR_{ground} values, which may be due to uncertainty of satellite data and temperature modelling.

Figure 3a. PLR_{ground} values with $PLR_{ref,ground}$ (red dashed line), the mean of the remaining (without outliers) PLR_{ground} values (dark) for module-3. Gray PLR_{ground} values are outliers. **b.** 60 $PLR_{satellite}$ values with $PLR_{ref,ground}$ for module-3.



- **Figure 4** shows the $PLR_{ref,ground}$ and $PLR_{ref,satellite}$ (mean of $PLR_{satellite}$ values) each module. For **module-3**, the $PLR_{ref,ground}$ and $PLR_{ref,satellite}$ are almost identical whereas for **module-1** and **module-2**, $PLR_{ref,satellite}$ values fall slightly outside of the 1σ band surrounding $PLR_{ref,ground}$. However, there are overlaps between the standard deviations computed for $PLR_{ref,ground}$ and $PLR_{ref,satellite}$ for the both modules. Considering the relatively large uncertainty associated to outdoor measurements, satellite-derived insolation data and long-term performance analysis, we do not spot major differences between the $PLR_{ref,ground}$ and $PLR_{ref,satellite}$ calculated for each module.
- This work demonstrates that an accurate long-term performance assessment using satellite-based monitored data instead of ground-based monitored data is in principle possible by computing the mean of various PLR values obtained from different data filtering methods and performance metrics.

Figure 4. Reference performance loss rates using ground- and satellite-based monitoring, $PLR_{ref,ground}$ and $PLR_{ref,satellite}$, of the three modules with their standard deviation.



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