Optimizing statistical sampling of in-situ PV module performance metrics for protection against plant total loss

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1. Motivation

PV module degradation and plant underperformance accumulate gradually and often go undetected by plant-level monitoring. Identifying real performance shifts requires objective, data-driven methods that answer two questions:

- *Has performance changed, and by how much?* — quantified via t-tests
- *When did it change?* — detected via Shewhart Control Charts

2. Monitoring Objective

Track temperature-corrected DC Performance Ratios (PR) for Pmp, Vmp, and Imp across a representative module sample equipped with GroundWork Module Monitors. Apply one-sided t-tests to determine whether the current population mean has fallen significantly below baseline:

Hypothesis test:

H_0: $\mu = \mu_0$ No change to baseline performance

H_1: $\mu < \mu_0$ Performance has decreased

where μ is the population mean DC PR and μ_0 is the baseline value (nameplate).

3. Sampling and metrics

a. Select a sample of modules that is representative of the target population. Initial power measurements routinely deviate from nameplate ratings, as shown in examples below.

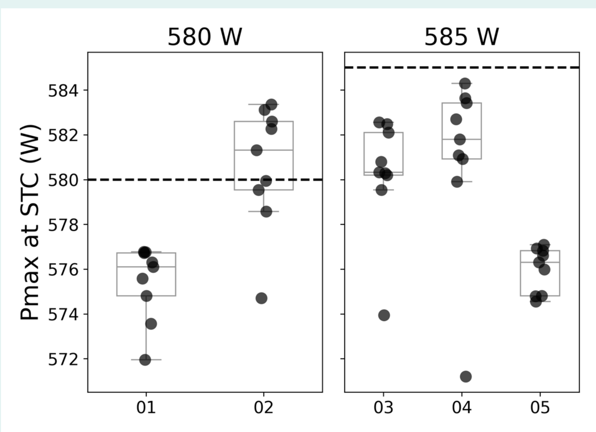

Fig 3.1: Modules sampled from pallets with different power classes

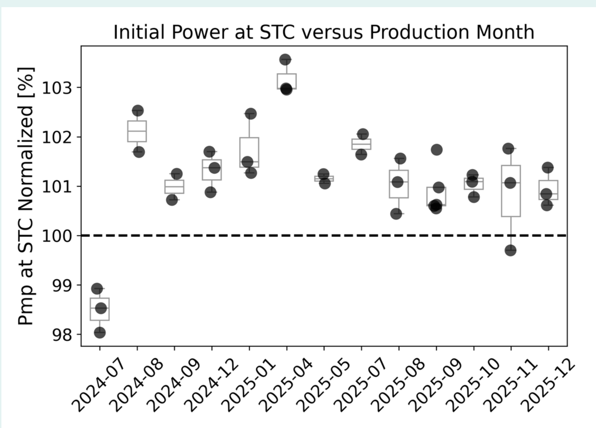

Fig 3.2: Modules sampled by production month

b. Deploy GroundWork Module Monitors for continuous IV curve sweeps alongside MET stations for weather data.

c. Compute daily DC PRs for Pmp, Imp, and Vmp.

$$PR_{Pmp\_DC} = \frac{\sum Pmp_{Tcorr} / Pmp_{NP}}{\sum EffIrr / 1000}$$

4. Shewhart Control Charts: Detect Shifts and Trends

When did the process change?

Shewhart control chart methods, adapted for longitudinal module-level monitoring, use repeated DC PR measurements to flag two distinct signatures: step-change shifts (special-cause events) and sustained degradation trends.

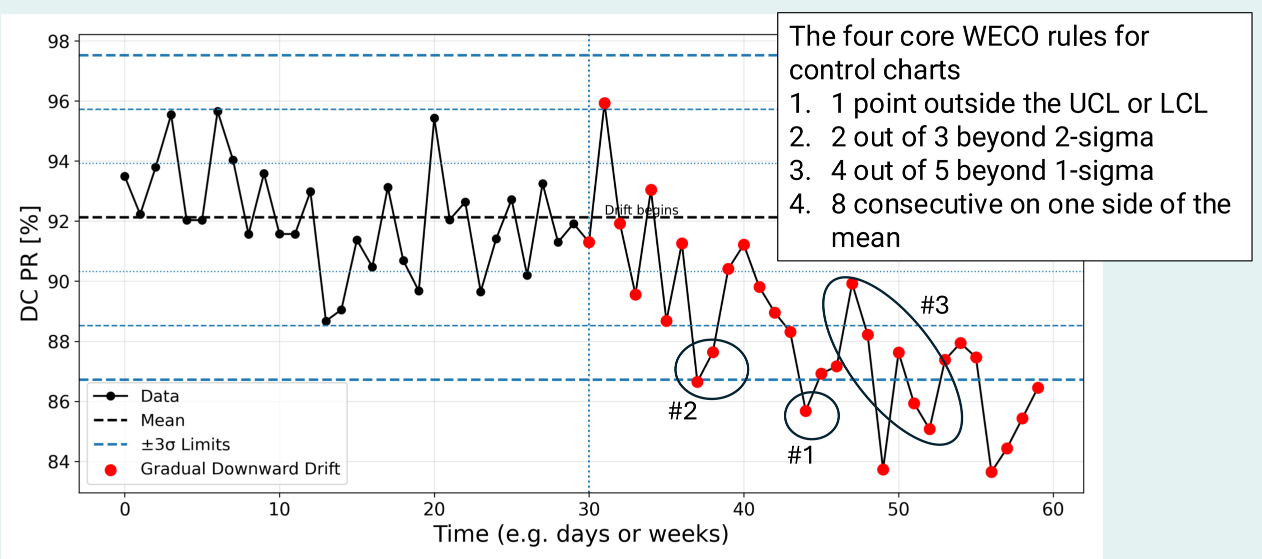

Fig 4. Shewhart control chart showing degradation and WECO rule violations

5. t-Tests: Quantify Delta to Nameplate

How large is the change?

$$t = \frac{\bar{x} - \mu_0}{s/\sqrt{n}}$$ Large negative *t* indicates underperformance

Is it statistically significant?

$p\text{-}value < \alpha$ Statistically significant decrease

$p\text{-}value \geq \alpha$ No significant evidence of a decrease

$\bar{x} = mean\ of\ the\ DC\ PR$

$\mu_0 = naemplate\ rating, i.e.\ 100\%$

$s = standard\ deviation\ of\ the\ individual\ PRs$

$n = number\ of\ modules\ in\ the\ sample$

$\alpha = significance\ level\ for\ assessing\ the\ deviation, e.g.\ 0.05$

6. Examples and Analysis

In the first example, module performance falls below the historical average beginning in early April, indicating a downward shift. Points remain within the lower limit for absolute measurement uncertainty, supporting high confidence in both the precision and accuracy of the metric.

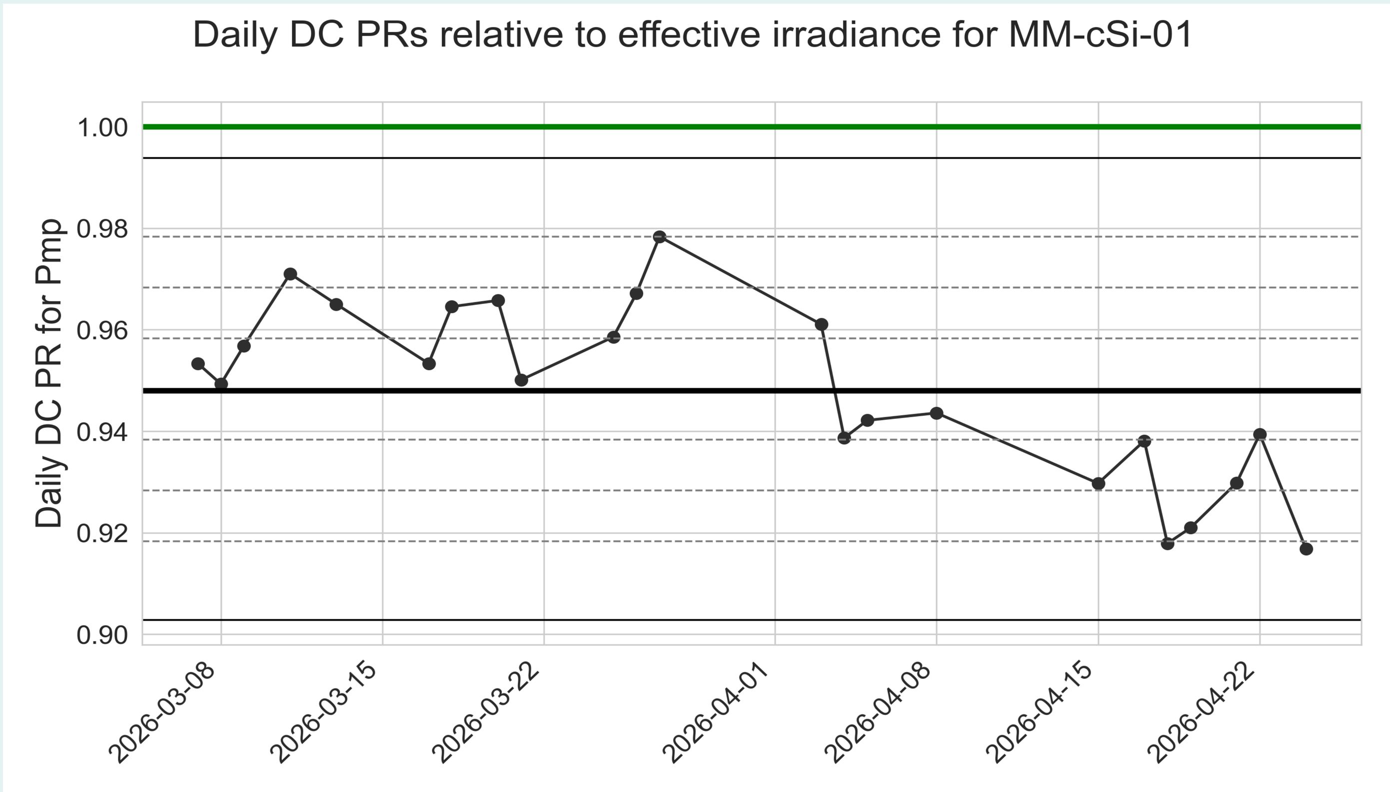

Fig 6a: Module DC PR drops below historical mean in April while remaining within measurement uncertainty bounds.

Power analysis shows that a sample of 15–16 modules achieves 95% power to detect a one-sigma shift in the mean using a one-sample t-test. A minimum sample size of 16 is therefore recommended.

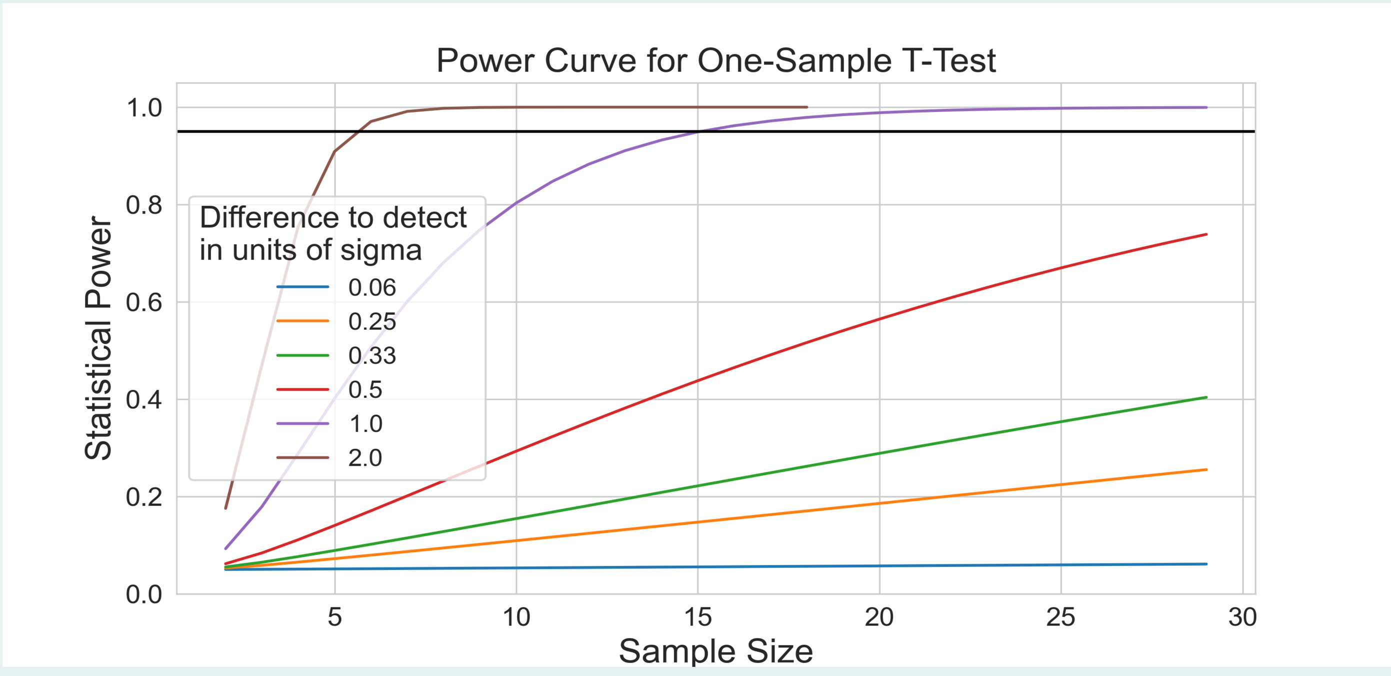

Fig 6b: Sample size determination

6. Examples and Analysis (continued)

The plot below simulates module degradation using rates informed by indoor lab testing. As modules degrade in the field, variability in the power distribution increases. The simulation applies 3% first-year degradation per the datasheet, followed by 1% annually — against a warrantied rate of 0.5% per year. Both the delta to nameplate and the delta to the warranty-defined expected value grow over time. The t-test compares measured power from a 16-module sample to the warranty-defined expected value. In this example, the additional 1% degradation beyond the warrantied rate is detectable after year one ($p < 0.05$), and likely sooner under monthly analysis.

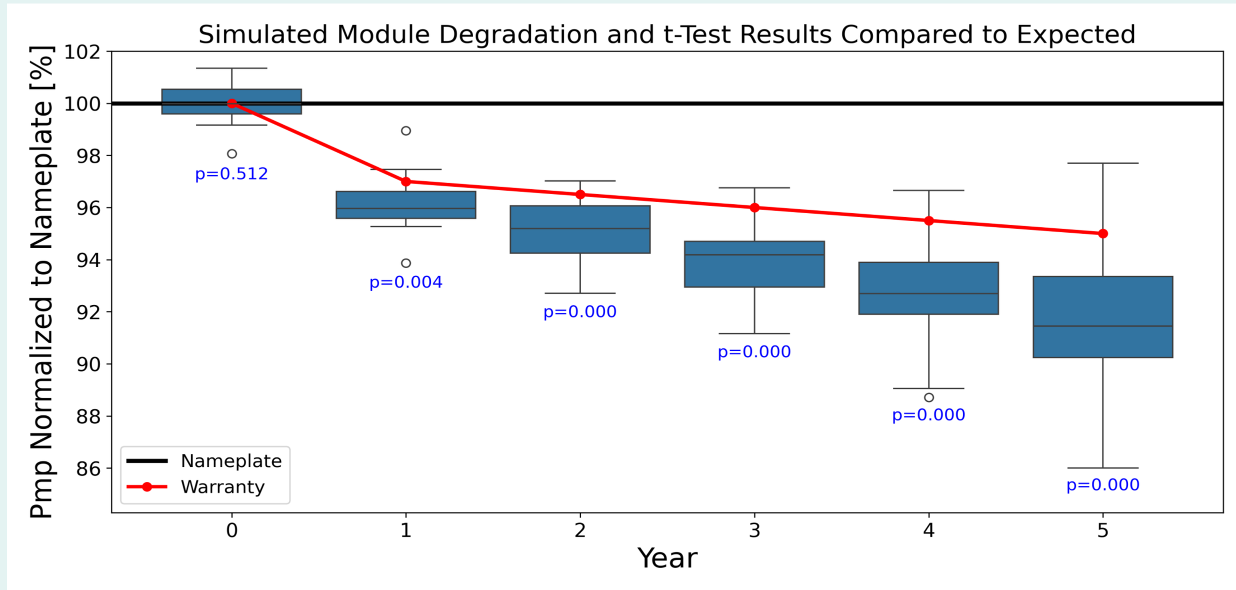

Fig 6c: t-Test p-values tracking 1% excess degradation against warrantied rate across 5 years

7. Process flow

1. Define a metric (e.g., temperature-corrected DC PR for Pmp, Vmp, Imp)
2. Select a representative module sample from the target population
3. Deploy GroundWork Module Monitors on the sampled modules
4. Merge performance data with MET station data to compute metrics
5. Define an aggregation window for DC PRs (daily or weekly)
6. Update control charts with new averages to identify special-cause variation
7. Run t-tests when a significant shift is detected across the majority of modules
8. Investigate root cause and take corrective action

8. Practical Guidance

- Use control charts for continuous monitoring and early detection
- Use t-tests to quantify the magnitude and significance of observed changes
- Maintain stable measurement practices to reduce false alarms
- Keep sample size at ($n > 16$)
- Review and update baselines and control limits periodically to reflect long-term conditions

9. Key Takeaways

A representative, adequately sized sample is the foundation of defensible statistical inference. Shewhart control charts identify *when* performance shifts occur. t-tests determine *whether* observed changes are statistically significant, separating signal from noise. Together, they provide a rigorous framework for performance assessment, O&M decision-making, and pre-warranty claim support. Data quality and sampling discipline are prerequisites for reliable conclusions.

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