Limitations of Commercial IV Curve Tracers for Field Evaluation of Modern Photovoltaic Modules

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Abstract

This study compares the use of five commercial IV curve tracers—three capacitive and two electronic-load—on high-efficiency bifacial half-cell photovoltaic (PV) modules. Outdoor measurements were performed on three PV modules with different cell technologies and wafer formats: (1) n-type M10, (2) p-type M10, and (3) p-type G12. Capacitive-load IV tracers showed systematic power shortfalls near the maximum-power point on devices with low V/I and/or higher intrinsic (diffusion) capacitance, consistent with transient effects that reduce fill factor. Increasing the effective load capacitance in one unit (parallel reconfiguration) extended the sweep time and markedly improved agreement with the electronic-load reference. A pre-test on the n-type module indicated that sweep times of at least ≥500 ms mitigates sweep-direction hysteresis; the electronic-load IV measurements were therefore used as reference. Overall, results showed that very fast sweeps can distort IV curves and reduce FF, whereas sweep profiles tuned to the device's V/I and capacitance recover the expected power. Practical implications are that adjustable-capacitance capacitive tracers or programmable electronic loads, coupled with sweep times short enough to limit environmental drift yet long enough to avoid transient bias, enable more reliable field IV testing of new-generation PV modules.

Keywords: Field Measurement, IV Curve Tracer, Outdoor Testing, High-efficiency Bifacial PV modules.

1. Introduction

The global photovoltaic (PV) sector has expanded rapidly, with over two-thirds of its installed capacity added in the past decade, and cumulative installed capacity reaching 2.5 TW in early 2025 (IEA-PVPS, 2025). Much of this expansion relies on higher-efficiency PV technologies, driven by a transition away from aluminum back surface field (Al-BSF) cells toward high-efficiency c-Si—PERC, TOPCon, HJT, and IBC—alongside module-level changes such as bifacial designs, half-cut cells, and larger wafer formats (VDMA, 2025). While these advances deliver higher efficiencies, many of these products still lack extended field operation, limiting insight into long-term performance and reliability. Accelerated indoor testing remains essential for identifying early failure mechanisms (IEA-PVPS, 2017); however, it does not fully replicate the diverse and dynamic stresses experienced outdoors. Outdoor characterization is therefore essential, especially in the early stages of adopting new PV technologies.

In this context, measuring the current–voltage (IV) curve is a key method for the electrical characterization of PV modules and arrays. It captures device behavior at given irradiance and temperature, revealing energy-conversion capability across operating points. From the IV curve it is possible to obtain essential parameters—short-circuit current (Isc), open-circuit voltage (Voc), and maximum power (Pmpp), together with the current (Impp) and voltage (Vmpp) at the maximum power point—which are key to assessing instantaneous performance and diagnosing faults, degradation, shading, or soiling (IEC, 2020; Lorenzo et al., 2023; Martinez-Moreno et al., 2011). Consequently, IV curve analysis is fundamental for commissioning, preventive and corrective maintenance, and comparative efficiency studies across technologies and installation configurations. When acquired with appropriate instruments and standardized procedures, IV curves provide an accurate view of a system's operational state and inform reliable maintenance and operational decisions (IEA-PVPS, 2017; Lorenzo et al., 2023; Martinez-Moreno et al., 2011).

Electrical characterization of PV devices and arrays is performed with IV curve tracers, typically grouped by load type—most commonly capacitive or electronic (Morales-Aragonés et al., 2021). Capacitive-load tracers generate fast sweeps by charging an internal capacitor through the module. The sweep time—the duration needed to capture a single IV curve from near Isc to Voc (or vice-versa)—depends on the device's voltage-current relation (larger V/I, i.e., lower current for a given voltage, yields longer sweeps; smaller V/I, i.e., higher current, yields shorter ones) and

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also scales with the effective load capacitance C, with larger C further extending the sweep..(Morales-Aragonés et al., 2021; *PVPM 1500X User Manual: Peak Power Measuring Device and IV-Curve Tracer for Photovoltaic Generators*, 2024). These instruments are simple and cost-effective but rely on low-ESR (equivalent series resistance) capacitors and adequate sampling; if the sweep is too short for high-capacitance PV devices, the IV curve can be distorted. Electronic-load tracers, by contrast, impose a programmed sweep via MOSFET/IGBT control, so the sweep time is set by the chosen profile rather than by a passive C–V/I constraint (Morales-Aragonés et al., 2021; Zhu and Xiao, 2020).

Overall, there is a practical trade-off: capacitive IV curve tracers emphasize speed and simplicity—very fast sweeps on the millisecond scale—whereas electronic-load tracers emphasize control (programmable current/voltage via MOSFET/IGBT) and, consequently, accuracy for high-capacitance PV devices; the appropriate choice therefore hinges on device capacitance and the allowable sweep time in the field (Morales-Aragonés et al., 2021; Pravettoni et al., 2021).

There remains a challenge in field measurement for high-efficiency modules. Devices with longer response times—typically associated with higher Voc and longer minority-carrier lifetimes—can exhibit transient charge effects when the bias changes rapidly during an I–V sweep, causing distortions near the maximum-power region, with systematic shortfalls in Pmpp reported under fast direct sweeps (Friesen and Ossenbrink, 1997; Pravettoni et al., 2021). As bifacial, half-cut, and large-wafer architectures proliferate, the interaction between device dynamics and the sweep profile (rate, direction, dwell/segmented scans) becomes increasingly important for reliable outdoor characterization. Taken together, these factors motivate a closer look at how load type and sweep dynamics affect outdoor IV measurements—and at what hardware or procedural adjustments are needed to obtain reliable results on modern high-efficiency modules.

To investigate how sweep profiles should be aligned with modern module behavior, five commercial IV tracers were compared—three capacitive and two electronic—on three bifacial half-cell modules spanning technology and wafer size (n-type M10, p-type M10, p-type G12). To directly probe sweep-time effects at the module level, one capacitive unit was reconfigured with a higher effective capacitance (capacitor bank in parallel) to extend the sweep window. Using the electronic-load platform as a reference, it was evaluated how sweep duration and load type influence outdoor IV-measurement fidelity, focusing on Pmpp, fill factor (FF), and cross-technology consistency. Accordingly, it was analyzed how sweep duration and load type influence outdoor I–V measurement accuracy in advanced PV modules.

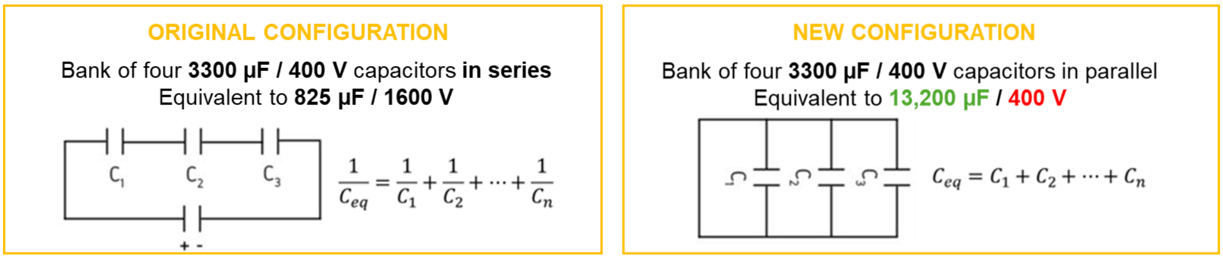
2. Methodology

To assess the accuracy of IV curve tracers on high-efficiency bifacial half-cell PV modules, field tests were carried out on three commercial bifacial modules, combining different cell technologies and wafer sizes: (1) n-type half-cut M10 (575 Wp), (2) p-type half-cut M10 (550 Wp), and (3) p-type half-cut G12 (645 Wp). The objective was to compare the performance of five IV tracers and analyze how sweep behavior affects results, particularly when measuring individual modules.

Three tracers used capacitive loads—two PVPM-1500X and one PVPM-1040X (PVE Engineering). They sweep the IV curve by charging an internal capacitor bank. The instruments use the four-wire method, avoiding systematic voltage-measurement errors from cable resistance. They are portable, battery-powered units that log irradiance from an external calibrated reference cell and module temperature via a rear-side PT100 RTD, with data export via USB. In the factory configuration, the effective sweep window is sub-second and depends on the device V/I ratio; for single-module tests this window is shorter. In this study, two units were used as supplied, and one PVPM-1500X was reconfigured (see below) to extend the sweep for module-level measurements. In the factory configuration, the PVPM-1500X is rated for up to 1500 V / 20 A, whereas the PVPM-1040X is rated for up to 1000 V / 40 A.

The PVPM equipment is widely used for IV curve tracing, and in its factory configuration, the capacitor bank is sized to deliver typical string-level sweep times of ~100–300 ms. The effective sweep time scales with the device V/I ratio: higher current and lower voltage yield a faster sweep. Because modern high-efficiency modules deliver high operating currents and exhibit non-negligible intrinsic capacitance, accurate single-module measurements generally require longer sweep windows to limit transient influence around the MPP. For strings, the impact of intrinsic capacitance on the IV shape is usually small. For single modules, however—operating at only a fraction of a string's voltage—the resulting sweep window is proportionally shorter, which increases sensitivity to acquisition parameters (notably near FF).

To extend the sweep window for module-level tests, the PVPM-1500X capacitor bank was reconfigured from series to parallel. In the original arrangement, four 3300 µF / 400 V capacitors in series provide an equivalent of ~825 µF / 1600 V; the new arrangement connects the same capacitors in parallel, yielding ~13 200 µF / 400 V (Figure 1). This increases the equivalent capacitance by up to 16x, enabling target sweep times ≈100 ms for single-module operation, while limiting the maximum operating voltage to ~400 V and thereby restricting use to module or short string measurements. A required firmware update was applied prior to the reconfiguration; no further hardware changes were introduced. The modified unit is shown in Figure 2 This alteration was carried out in collaboration with the device developer, such modification must not be implemented without proper guidance and approval from manufacturer.



(a) (b)

Figure 1: Schematic of the PVPM1500X modification: (a) original equipment configuration and (b) new configuration.

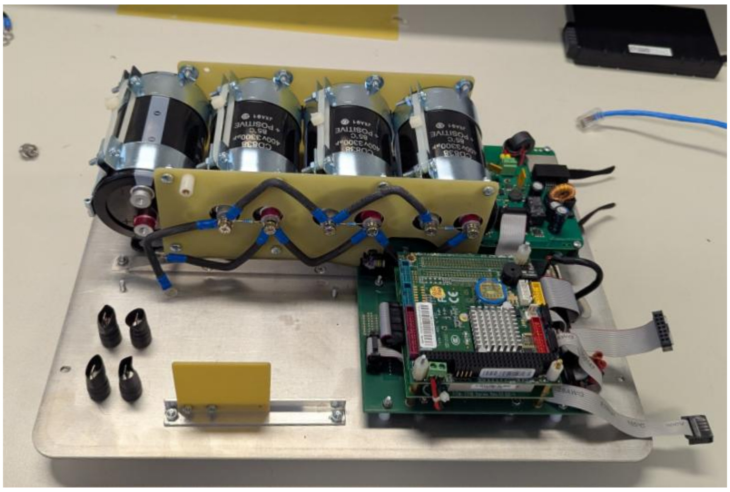


Figure 2: Photo taken during the capacitor reconfiguration of the PVPM-1500X IV curve tracer.

The fourth tracer, the modular electronic-load equipment PV-Blocks by ReRa Solutions, served as a reference (ReRa Solutions BV, 2025). Its IV/MPP module provides a programmable load with current ranges up to 40 A and a fixed voltage range defined by the hardware configuration. Various voltage range options—5, 40, 80, or 200 V—are available to optimize accuracy for each module type, enabling precise control of sweep rate, direction, and dwell or segmented profiles during single-module outdoor testing. It was first exercised forward and reverse sweeps across multiple rates on the n-type module (higher intrinsic capacitance out of the tested PV modules) and selected the configuration that minimized hysteresis—i.e., forward–reverse mismatch due to device capacitance interacting with sweep dynamics, sometimes reinforced by minor irradiance/temperature changes. This sweep configuration was then used for all subsequent measurements. Although designed for high-accuracy characterization under outdoor conditions, the system is non-portable, which limits its use for distributed measurements across multiple points, such as in a PV plant.

A fifth portable tracer, the h.a.l.m. cetisPV-LC1, was also tested. This device employs a hybrid approach, featuring an electronic load for low-voltage measurements and an additional capacitive load to extend the voltage measurement range. Despite its age and the lack of recent calibration, this equipment was tested alongside newer devices in the electronic load configuration for single-module measurements, leveraging its load characteristics.

The test campaign took place on the premises of the laboratory Fotovoltaica UFSC, in Florianópolis, Brazil (27.4° S, 48.4° W), on a clear, cloudless day between 12:00 and 13:00 (local time). The modules were positioned in the same plane and orientation, at ~30° tilt, facing geographic north. Plane-of-array irradiance was measured with a calibrated crystalline-silicon reference cell, and the same sensor was used for all acquisitions to ensure consistency. Measurements were taken sequentially—each module was tested in turn with all five IV tracers—to minimize environmental variation during the series. Prior to data collection, the modules were exposed to sunlight for several minutes to stabilize temperature. The modules were measured with their rear sides covered, eliminating uncertainties associated with rear-side irradiance compensation (Pires et al., 2024).Module temperature was monitored with a thermal imager (FLIR E54). The field setup and instrumentation are shown in Figure 3.

(a)

(b)

(c)

Figure 3: Field setup and instrumentation. (a) PVPM tracers used for capacitive sweeps (two PVPM-1500X and one PVPM-1040X) and h.a.l.m. cetisPV-LC1 IV tracer with electronic load (b) PV-Blocks electronic-load IV module. (c) PV-Blocks control and data-acquisition units for electronic-load channels.

3. Results

Before the comparative campaign, PV-Blocks was used to evaluate sweep-time sensitivity on an n-type module (higher intrinsic capacitance) (see Figure 4). Sets of IV curves were acquired at sweep times of 50 ms, 500 ms, 1 s, 2.5 s, and 5 s in forward and reverse directions. Sweeps ≥ 500 ms produced near-overlapping traces within repeatability, with consistent Pmpp and FF, whereas the 50 ms sweep showed a clear deviation near the knee, indicative of transient bias and reduced apparent Pmpp. Accordingly, 500 ms was selected as the PV-Blocks reference profile for subsequent tests—minimizing hysteresis while keeping the acquisition window short enough to limit potential irradiance and temperature changes during outdoor operation.

Figure 5 summarizes the results obtained with the five tracers across the three module types. Measurements for each module were taken sequentially—one tracer after another within roughly five minutes, which kept environmental variability within a series small; module temperature varied by at most 1 °C. To avoid adding uncertainty from normalization, the analysis reports measured powers directly, without STC correction, so that observed differences can be attributed primarily to instrument behavior.

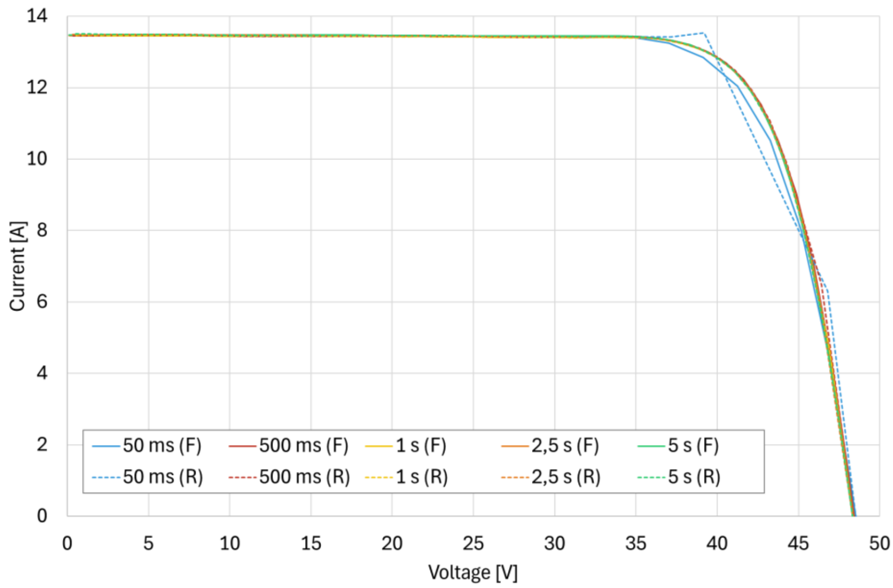
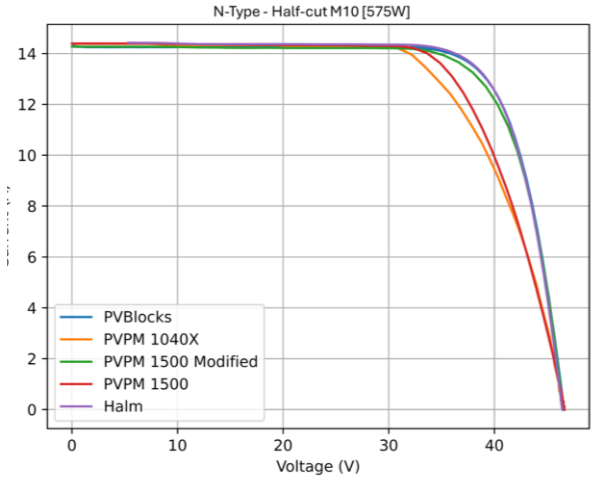
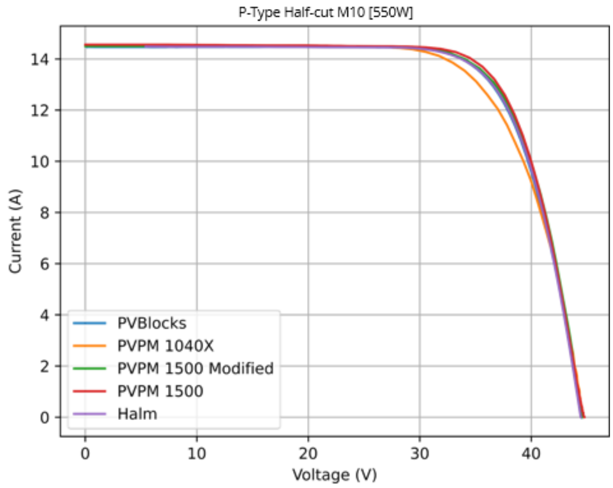


Figure 4: Sweep-time sensitivity on an n-type module (PV-Blocks, forward and reverse sweeps). IV curves acquired at sweep times of 50 ms, 500 ms, 1 s, 2.5 s, and 5 s.



(a)



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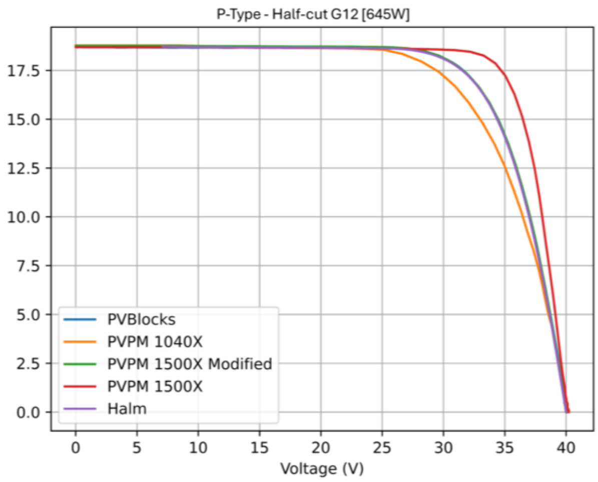

(c)

Figure 5: IV curves of the modules measured with five tracers: (a) n-type half-cut M10 (575 Wp), (b) M10 p-type (550 Wp), and (c) half-cut G12 p-type (645 Wp).

Table 1 lists the power measured by each tracer and the percentage error relative to PV-Blocks, used as the reference due to its electronic load and precise control of sweep parameters. As shown in Figure 5, Voc and Isc were consistent among all tracers, indicating reliable capture at the curve extremes. Differences emerge mainly in the mid-curve region near the MPP, where sweep dynamics are most influential. Very fast sweeps can prevent the device from reaching steady state at each operating point, producing transiently distorted traces, reduced FF, and lower measured power.

Table 1: Measured power values for each of the three PV modules using different IV curve tracers. No STC normalization was applied—values are reported as measured—so differences mainly reflect instrument behavior.

PV Module Cell Type		half-cut M10 [575 Wp]	half-cut M10 [550 Wp]	half-cut G12 [645 Wp]
PVPM 1040X	P [W]	450,4	460,7	516,3
	Error [%]	12%	4%	7%
PVPM 1500X	P [W]	475,2	487,8	611,5
	Error [%]	8%	2%	11%
PVPM 1500X (Mod.)	P [W]	503,3	481,7	553,4
	Error [%]	2%	1%	0%
Halm	P [W]	524,2	493,8	568,6
	Error [%]	2%	3%	3%
PVBlocks (REF)	P [W]	514,0	477,6	553,0
	Error [%]	0%	0%	0%
STC	Isc [A]	14,3	14	18,35
	Voc [V]	51,15	49,9	44,8
	Voc/Isc	3,58	3,56	2,44

For the n-type M10 half-cut (575 Wp) module, PV-Blocks measured a peak power of 514.0 W. The modified PVPM-1500X (extended capacitance) produced 503.3 W (−2%), within the ~5% estimated uncertainty. The PVPM-1500X in the default configuration and PVPM-1040X underestimated power by −8% and −12%, respectively, consistent with shorter effective sweep windows on high-capacitance devices. The Halm tracer agreed closely with the reference, showing a +2% deviation relative to PV-Blocks.

For the p-type M10 half-cut (550 Wp) module, peak power errors were smaller: +2% (PVPM-1500X in the default configuration), +1% (modified PVPM-1500X), and −4% (PVPM-1040X)—all within or very close to the uncertainty band. This suggests that p-type M10 modules are less sensitive to fast sweeps; their lower current relative to larger-format devices yields a more favorable V/I, effectively allowing longer practical sweep times with a capacitive load and improving agreement among tracers. Halm results remained close to reference as well, at about +3% vs PV-Blocks.

For the p-type G12 half-cut (645 Wp) module, the modified PVPM-1500X and PV-Blocks delivered nearly identical peak power measurements (553.4 W and 553.0 W). In contrast, the PVPM-1040X underestimated by ~7%, while the PVPM-1500X in the default configuration overestimated peak power by ~11%. Despite sharing p-type technology with the 550 Wp device, the larger G12 cell area leads to higher current and a less favorable V/I, making results more sensitive to sweep-time choices. For this module, Voc/Isc ≈ 2.434 V/A, substantially lower than ≈ 3.564 V/A for M10 devices, which naturally shortens the effective sweep for a fixed capacitive load and can compromise measurement quality if sweep-time control is limited. The Halm tracer again tracked the reference closely, with a +3% deviation relative to PV-Blocks. It is important to note that the Halm tracer showed good agreement with the reference in all measurements across all tested modules, despite its age and the absence of recent calibration. However, it requires a connected computer and a relatively involved setup, making outdoor deployment less practical than dedicated field IV tracers.

The n-type M10 module had Voc/Isc ≈ 3.578 V/A, close to the p-type M10 value, yet its behavior differed—indicating two concurrent mechanisms that limit fidelity under fast capacitive sweeps: intrinsic (diffusion) capacitance in the n-type case and V/I-driven sweep compression in the G12 case. Both mechanisms reflect the same underlying limitation of very fast acquisition on certain modern modules but through distinct pathways.

Overall, the results emphasize the importance of aligning sweep parameters with device characteristics. While laboratory setups provide fine control of sweep profiles, many field instruments reflect assumptions from earlier module generations. For single-module measurements—in which lower voltage and higher current compress the effective sweep—providing user-adjustable sweep settings and the option to increase the effective capacitive load (thereby extending the sweep window) can materially improve curve fidelity. Consistent with these findings, PV-Engineering now offers a modified single-module tracer as a standard option (PVPM2540X; 250 V, 40 A) that provides extended sweep capability for module-level measurements; however, this instrument became available only after the present campaign and was therefore not included in the comparison.

4. Summary and Conclusions

This work compared five commercial IV tracers—three capacitive (two PVPM-1500X and one PVPM-1040X), one electronic-load system (PV-Blocks), and one hybrid device with an electronic load for low voltage measurements and an additional capacitive load for extension of voltage range (halm)—on three bifacial half-cell modules with different PV technologies and wafer sizes (n-type M10, p-type M10, p-type G12). A pre-test on the n-type device established 500 ms as optimal sweep time for PV-Blocks programable measurements (minimal hysteresis with a short acquisition window). Under clear, stable outdoor conditions, Voc and Isc were consistent among instruments, while differences emerged near the MPP. For the n-type M10 and the p-type G12, very fast capacitive sweeps compressed the effective acquisition window and interacted with intrinsic/diffusion capacitance, reducing FF and Pmpp. Reconfiguring one PVPM-1500X with its capacitor bank in parallel (higher effective capacitance, module-level voltage range) extended the sweep and improved agreement with the electronic-load reference. The p-type M10, with a more favorable V/I, showed smaller sensitivity to sweep speed.

Overall, the results indicate that sweep parameters must be aligned with device characteristics, particularly intrinsic capacitance and V/I ratio, which are technology- and wafer-format dependent. For single-module measurements—lower voltage and higher current—longer sweep windows are often required; this can be achieved by increasing effective capacitance in capacitive tracers (within safe voltage limits) or by using programmable electronic-load profiles. These adjustments improve curve fidelity around the MPP and produce power and FF values that better reflect true device performance.

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