# PACT Perovskite PV Module Outdoor Test Protocol

Version 0.2

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# 1. Introduction

The purpose of this protocol is to define procedures and practices to be used by the PACT center for field testing of metal halide perovskite (MHP) photovoltaic (PV) modules. The protocol defines the physical, electrical, and analytical configuration of the tests and applies equally to mounting systems at a fixed orientation or sun tracking systems. While standards exist for outdoor testing of conventional PV modules, these do not anticipate the unique electrical behavior of perovskite cells. Further, the existing standards are oriented toward mature, relatively stable products with lifetimes that can be measured on the scale of years to decades. The state of the art for MHP modules is still immature with considerable sample to sample variation among nominally identical modules. Version 0.0 of this protocol does not define a minimum test duration, although the intent is for modules to be fielded for periods ranging for weeks to months. This protocol draws from relevant parts of existing standards, and where necessary includes modifications specific to the behavior of perovskites.

> *Note:* the initial version 0.0 of this protocol has not been tested or validated with a wide range of MHP PV modules. The initial protocol has been designed with knowledge based on laboratory testing of perovskite cells and modules and field testing of other technologies. This protocol will be revised as updated as PACT tests the approach and validates against field data.

# 2. Definitions and References

*Definitions:*

- **Module** – weatherproof package containing multiple, interconnected solar cells that can be electrically connected to an external load
- **MHP** – Metal Halide Perovskite
- **MPPT** – maximum power point tracking
- **RTD** – Resistance Temperature Device
- **PV** – Photovoltaic

*References:*

- IEC 60904-1: Measurement of photovoltaic current-voltage characteristics
- IEC 60904-2: Requirements for reference solar devices
- IEC 61724-1: Photovoltaic system performance – Part 1: Monitoring

# 3. Requirements for outdoor testing location

The testing location shall be free from shading and reflections from nearby buildings, windows, poles, vehicles, or other test structures. If using a sun tracker, it is important to also consider the views to the east and west. If using a normal incident sun tracker, structures to the north of local latitude shall also be considered. The site shall have easy access for daily inspection and periodic instrument cleaning. The site shall preferably have access to AC power and wired network interconnect. In locations with snow, a fixed camera or frequent inspection shall be implemented. Inspection shall be implemented at a frequency adequate to determine when modules or other instruments are blocked or partially obscured by snow.

# 4. Test equipment

Required equipment includes the mounting structure, electrical measurement and temperature of each sample, local reference irradiance and ambient temperature. Optional equipment includes reference PV devices held under substantially identical conditions as the test samples and local site weather.

*Required:*

- **Mounting structure:** The mounting structure shall be a free-standing rack properly sized to securely hold samples. Mounting structures shall be configured to avoid interference with wiring, pottant or back of module temperature measurement. The mounting structure shall be securely anchored to avoid overturning due to high winds. Clamping hardware or module clips shall be sized to avoid overlapping any module active area. Clamping hardware shall be secure enough to prevent samples from detaching during high wind and durable enough to withstand several months of outdoor exposure, including high UV.

    1. **Fixed tilt system:** Tilt angle shall be at local latitude tilt, or alternatively, adjustable to maximize seasonal solar exposure. The azimuthal alignment shall be toward the equator to within ~1°.

    2. **Sun tracking system:** A sun tracking system may optionally be used in place of a fixed tilt system to enhance solar exposure. An automated normal incident tracker similar to that used for solar resource measurements is preferred. However, horizontal or inclined single axis trackers, up to and including polar trackers may also be used.

- **Electrical Measurement:** Electrical measurement equipment includes a combination of DC voltage and current measurement combined with a controllable load that can bias each sample from Voc to Isc or any chosen point in between. Voltage and current measurements shall be capable of operating concurrently with load control and may be integral to it.

    1. **Voltage measurement:** Voltage measurement shall have a full-scale range that exceeds expected sample Voc by at least 20% and a minimum resolution of 0.01% of expected sample Voc. Accuracy shall be ±0.1% or better across the selected range (% of reading + % of range).

       *Note:* for this initial draft, sample Voc may be estimated by multiplying 1V by the number of series cells if sample Voc has not been determined from indoor characterization. See Section 5.

    2. **Current measurement:** Current measurement shall have a full-scale range that exceeds expected sample Isc by at least 50% have a minimum resolution of 0.01% of expected Isc. Accuracy shall be ±0.1% or better across the selected range (% of reading + % of range).

       *Note:* for this initial draft, sample Isc may be estimated by multiplying 20 $mA/cm^2$ by the area of a single cell (in $cm^2$) if sample Isc has not been determined from indoor characterization. See Section 5.

3. **Controllable load:** The controllable load shall have at least two modes of operation; 1). full IV sweep between Isc and Voc and 2). maximum power point tracking. For testing to this protocol, maximum power point tracking shall be the most frequently used mode.
   - IV sweep mode shall operate by voltage control and be capable of operating at user-specified slew rate in V/s. Slew rate shall have a range from 0.20 - 2V/s per cell in series. Current voltage measurements during IV sweeps shall be at a rate sufficient to acquire a minimum of 100 points per curve. IV sweep mode shall be capable of operating in either the forward (Isc to Voc) or reverse (Voc to Isc) direction.

     Alternative to a continuous voltage slew, IV sweep mode may utilize discrete voltage steps followed by a constant voltage dwell. If such a mode is used, it is recommended that voltage and current measurements are made concurrent with the voltage dwell.

     *Note:* Requirements for IV sweep measurements pertain to "fast-IV" measurements only. Methods such as the "Asymptotic Pmax" scan are beyond the scope of this protocol.

   - MPPT mode shall use a perturb and observe algorithm with user-specified voltage steps and step frequency. Minimum settable voltage step size shall be no greater than 0.1% of estimated sample Voc and a maximum of no less than 1% of estimated sample Voc (see note above under Voltage Measurement). Step frequency shall be 1 Hz. It is recommended to have a range from 0.10 – 10 Hz.

     *Note:* Requirements for MPPT pertain to equipment capabilities and are not guidance for initial settings.

   - Regardless of mode or settings, the load shall be capable of continuously dissipating 25% greater power than the product of expected Voc and Isc

4. **Automated control:** it is preferred that the measurement system be capable of automatically switching between load and measurement modes according to a predetermined schedule. It is also preferred that the system be capable of switching between nighttime and daylight modes according to predetermined metrics.

5. **Run time and data storage:** The measurement system shall be capable of continuous 24-hour operation with minimal interaction. Local data storage is recommended but not required.

- **Reference irradiance:** Reference irradiance shall be measured using a spectrally flat, Class A pyranometer mounted coplanar with the sample.

- **Sample temperature:** Sample temperature shall be measured via a surface sensor, adhered to the rear of the sample, directly underneath the active area. Measurement accuracy shall be ±1°C or better.

- **Ambient temperature:** Ambient temperature shall be measured near the sample mounting structure. The device shall be protected from direct solar radiation and radiation reflected from walls or other sources of heat. The device shall be exposed to unrestricted airflow.

*Optional:*

- **Reference PV device:** An optional reference PV device may be mounted in the test plane adjacent to the sample. The reference PV device shall use a known stable PV cell type (e.g., c-Si), be considered "linear" and have electrical properties that are similar to the sample. The reference device shall be held in the same electrical state as the sample. This reference device is considered a "witness", experiencing the same conditions as the sample, and is not a substitute for an irradiance reference.
- **Site weather station:** In addition to locally measured plane of array irradiance and ambient temperature, it is advisable to have a comprehensive site weather station. The site weather station may range from a compact all-in-one design to a more advanced design with separate instruments. Typical quantities measured will include DNI, GHI, DHI, wind speed at 10 m, ambient temperature, precipitation, and relative humidity. If the measurements are to be used for computational analysis, it is recommended to use a more advanced design employing Class A instruments.

# 5. Sample inspection and documentation

Sample inspection and documentation may be performed as part of a separate intake protocol. At a minimum, the following steps shall be performed in preparation for outdoor testing.

- **Visual Inspection:** Verify module is identified by an adhesive label bearing PACT lot and sample number, e.g., P-0001-07 (Batch 1, Sample 7). Verify label does not obscure any portion of the active area. Examine wires and connectors for integrity. Examine the module package for evidence of damage or inconsistent assembly. Identify active area via inspection of rear-side metallization or identification of other demarcation. Examine MHP absorber within active area for evidence of pinholes, non-uniform film coating or other visual defects.
- **Photographic Documentation:** Utilize a copy stand and stationary camera to document the front and rear each sample. Include a reference ruler measurement for validation of sample active area. Ensure camera working distance and zoom (if available) are set such that the sample substantially fills the field of view without excluding any features. Saved images shall use a naming convention of [Batch]-[Sample]_[YYYYMMDD]_[F or R].
- **Active Area:** Calculate active area in $cm^2$ by measuring the width of the cells parallel to the scribe line and the length of the sample perpendicular to the scribe line, from the first to last active cell. Count the number of active cells. Calculate the area of a single cell by dividing the total Active Area by the number of cells.
- **Estimate Voc and Isc:** Calculate target upper bounds for open circuit voltage (Voc) and short circuit current (Isc). Multiply the number of active cells by 1V to determine target Voc and the area of a single cell by 20 $mA/cm^2$ to determine target Isc. These values are to be used as a relative assessment of minimodule health and as a guide for configuration of measurement equipment.

*Note:* Guidance for normalized cell properties were approximated by rounding down the Voc and Jsc for a perovskite minimodule with record efficiency listed in Table 1 of "Solar cell efficiency tables (Version 60)"

- **Initial Electrical Behavior:** Using a hand-held digital multimeter, verify correct polarity of the connector installed on each minimodule by measuring voltage under typical room light. For any sample with reversed polarity, do not proceed with further electrical characterization until polarity is corrected. Affix each sample to the temperature-controlled chuck of a calibrated cell simulator. Measure Voc, followed by Isc under STC. Minimize exposure to high intensity simulator light greater than $50W/m^2$.

  *Note:* Voltage >1V should be easily obtainable for multicell devices at typical lighting levels of 250-500 lux.

## 6. Outdoor test details

During outdoor testing, samples shall be exposed to environmental and operating conditions that are typical of those that any commercial PV technology must be capable of enduring. Contemporary commercial PV products are engineered to function for 20 years or longer. Perovskite modules do not yet display this level of maturity and may last days to weeks, or in some cases only hours. A minimum test duration is not prescribed by this protocol; however, it is intended that modules shall experience full diurnal cycles until the test is determined to be concluded. Samples shall primarily be held at a maximum power bias condition. Intermediate IV sweeps or Isc-Voc measurements are considered optional.

*Preparation and mounting*

- Because of the potential for very short module lifetime after initial exposure to sunlight, samples shall not be installed on the mounting system until all preparations, including instrumentation configurations have been made.
- To ensure that maximum data can be obtained on short-lived samples, it is preferred to initiate outdoor testing on a clear day, as early in the day as possible. As module maturity progresses, this recommendation will become obsolete.
- Attach temperature sensor to the back surface of the module, directly underneath the active area using an appropriate adhesive. Most commonly, the adhesive will be an integral part of the chosen sensor.
- Ensure data acquisition system is set up with proper measurement intervals, MPPT mode and optional intermediate measurements specified.
- Mount each module under test to the racking system. Ensure the sample is securely fastened to the structure and will not move as the result of high winds, or other natural forces. Care should be made to not damage the module by over torquing module clips.
- Ensure sample and temperature measurement connectors are securely plugged into their respective measurement channels.

*Startup and testing*

- Remove cover, if used and initiate MPPT and measurement.
- Maximum power tracking shall be maintained during defined daylight hours. The preferred method of determining "daylight" includes establishing sunrise/sunset times or sun position relative to the horizon using published algorithms. Sun position 2° above the horizon is a useful starting point, however this may be adjusted to account for local topography. Optionally, an irradiance threshold of 20 $W/m^2$ may be used.
- During defined nighttime periods, active maximum power tracking shall be disabled. As of this initial draft, there is not universal consensus as to the proper bias state that should be maintained overnight. PACT preference had been to maintain a shorted condition. In January 2025 PACT updated that preference to an open circuit condition. Regardless of which is chosen, overnight bias condition shall be documented.
- The monitoring system shall continue to collect ambient weather data and module temperature during overnight periods.
- Continue monitoring until the sample is determined to have reached the end of useful life. End of life is often accepted to be when power has dropped to 80% of it's initial value. However, given the state of perovskite maturity, it may be beneficial to continue monitoring as the module drops to 10% of initial power or lower.
- At the conclusion of outdoor testing, disable MPPT and discontinue data monitoring. Remove and store sample for any future diagnostic testing.

*Observation during testing*

- Immediately after startup, access the measurement system and observe electrical properties. It is advisable to verify proper operation and configuration within a few minutes of startup.
- Observe operation periodically during the first 1-3 hours and occasionally during the first 24 hours. If a module displays a rapid drop in power, it may be advisable to terminate testing.
- During the first week of operation, properties shall be observed at least daily. It is preferred to observe more frequently if practical.
- After 2 weeks of operation, observation frequency may be reduced, however it is advisable to continue observing at least 3x per week.
- Samples shall be visually inspected at least daily during the first week of testing for any signs of cracking, seal failure, cell discoloration or other visual anomalies.
- A record of site conditions that are not captured by the measurement system shall be kept. Such events may include snow or ice storms, hail or wildfire smoke.

## 7. Measurement specifications

- **Maximum Power Point Tracking:**

1. The initial voltage for maximum power point tracking shall be 70% of Voc measured at STC in Section 5 of this protocol, or estimated as in Section 4.1
2. The MPPT voltage step size shall be equal to 1% of Voc measured at STC, as above.
3. The time interval between voltage steps during MPPT shall be 1.0 seconds

- **Recording Interval:**
  1. Voltage and current shall be recorded at an interval of 1 minute or less.
  2. Recorded values may include a single measurement at a frequency of 1/minute or faster or an average of higher frequency sampling.
  3. Irradiance, sample temperature and ambient temperature shall be recorded at the same frequency as voltage and current.
- **IV Sweep Interval:**
  1. The impact and practicality of performing in-situ IV sweeps on fielded perovskite modules under potentially variable irradiance conditions is unknown as of Version 0.0 of this protocol.
  2. Measurement intervals shall be no more frequent than once per hour.
  3. Measurement intervals may follow a regular time step or be initiated according to predefined conditions having been achieved, e.g., irradiance > 800 W/m$^2$.

## 8. Version History

- Version 0.1 – 5/5/2023 - Initial Release
- Version 0.2 – 3/27/2025 - Changed nighttime preference for modules from short circuit to open circuit.

PACT