PV Module Manufacturing and Testing

Industry Requirements for Perovskite PV Modules

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INTRODUCTION

What standard tests are required for commercializing a new PV module technology such as perovskite photovoltaics? This summary document provides answers in the areas of (1) quality assurance for manufacturing, (2) safety and reliability testing, and (3) performance characterization.

This report was prepared by the Perovskite PV Accelerator for Commercial Technologies (PACT) center's Bankability team, led by Black & Veatch. It summarizes the quality, reliability, and performance testing and certifications required for selling photovoltaic modules in the United States. This document only provides an overview of these standards. Interested parties should follow the guidance provided in the original referenced standards and protocols.

We have queried industry professionals about what accommodations have been made to include perovskite PV modules in quality, safety, reliability and performance standards and have been informed that there have not been any suggested perovskite-specific changes/amendments to these standards to date. It is important to note that pre-commercial perovskite PV modules that can be manufactured consistently and survive basic outdoor exposure are a prerequisite for standards development. PACT is actively working with academic and industry research groups to help them demonstrate this prerequisite module performance and reliability. PACT is committed to working with a diverse set of stakeholders to help evaluate this technology in a fair and neutral fashion.

1. QUALITY MANAGEMENT FOR PV MANUFACTURING

This section provides an overview of quality management systems employed by companies in the PV manufacturing industry. We identify the following international standards to be relevant in implementing a quality management system for perovskite PV module manufacturers:

- ISO 9001:2015 – Quality Management Systems
- IEC 62941:2019 – Terrestrial photovoltaic (PV) modules – quality system for PV module Manufacturing

1.1. ISO 9001

ISO 9001 is an international standard that defines requirements for a quality management system. ISO 9001 is used by manufacturers to demonstrate the ability to consistently provide products and services that meet customer and regulatory requirements. ISO 9001 provides a process-oriented approach to documenting and reviewing the structure, responsibilities and procedures required to implement an effective quality management system in manufacturing. ISO 9001 provides information on the following topics:

- Determining the scope of the quality management system;
- Quality management system and its processes;
- Leadership and commitment;
- Establishing and communicating the quality policy;
- Organizational roles, responsibilities and authorities;
- Actions to address risks and opportunities;
- Quality objectives and planning to achieve them;
- Monitoring and measuring resources;
- Control of documented information;
- Requirements for products and services;
- Design and development of products and services;
- Product identification and traceability;
- Monitoring, measurement, analysis and evaluation;
- Nonconformity and corrective action; and
- Continual improvement.

We note that ISO 9001 applies to any organization, regardless of size or industry.

1.2. IEC 62941

While ISO 9001 is used as an international standard for documenting quality management systems, it addresses generic elements of a quality management system and does not cover specific details of interest to the PV industry. The PV Module Quality Assurance Task Force (PVQAT) has focused on the requirements of a quality management system used to guide the consistent manufacturing of PV modules and has developed IEC 62941, a PV-specific supplement to ISO 9001, that strengthens the quality management system by incorporating known requirements for PV. Some key requirements addressed in IEC 62941 include:

- Focus on the manufacturer's control of the PV module's design to align the expected lifetime with its relationship to the manufacturer's warranty. Warranty claims must be addressed by product and process design or by financial means;
- Requirement to ensure the manufacturer has considered potential failure modes (i.e., through a Failure Modes and Effects Analysis, FMEA) and has taken steps to address those in the design, production, application and delivery process;
- Requirement to obtain IEC product certification and implement an ongoing reliability test program that monitors PV modules' performance for compliance with standards and the stated design lifetime;
- Requirement to improve product traceability through the entire supply chain to enact positive control of the product for recalls and warranty claims;
- Design of a manufacturing process that will ensure conformance to the design intent for performance, lifetime, and warranty; and
- Special processes, such as control of solderability, electrostatic discharge (ESD) control, and assignment of PV module power rating.

The objective of IEC 62941 is to provide a framework for the improved confidence in the ongoing consistency of performance and reliability of certified PV modules. The requirements of this standard are defined with the assumption that the quality management system of the manufacturer has already fulfilled the requirements of ISO 9001 or an equivalent quality management system.

IEC 62941 is applicable to all PV modules independent of design and technology, i.e., perovskite PV technologies. We note that quality controls for perovskite and other nonconventional PV technologies will differ somewhat from those of more conventional designs and further notes that IEC 62941 has not explicitly considered these differences.

2. REQUIREMENTS FOR SAFETY AND RELIABILITY TESTING

This section provides an overview of the safety and reliability testing protocols for PV modules. We recommend that testing is performed by a Nationally Recognized Testing Laboratory (NRTL) such as UL, CSA, Intertek, or TUV.

2.1. Safety Testing

Safety testing covers regulatory requirements for commercial PV modules. We have identified the following international safety standards to be relevant for perovskite PV module manufacturers:

- IEC/UL 61730-1 – Photovoltaic (PV) module safety qualification – Part 1: Requirements for construction
- IEC/UL 61730-2 – Photovoltaic (PV) module safety qualification – Part 2: Requirements for testing

2.1.1. IEC 61730-1

This part of IEC 61730 specifies and describes the fundamental construction requirements for PV modules to provide safe electrical and mechanical operation. This standard provides a framework to assess the prevention of electrical shock, fire hazards, and personal injury due to mechanical and environmental stressors encountered during construction. Some key requirements addressed in IEC 61730-1 include the following:

- PV module classification, applications and intended use;
- Requirements for design and construction;
- Electrical components and insulation;
- Mechanical and electromechanical connections; and
- Protection against electric shock.

The objective of IEC 61730-1 is to define the requirements for the construction of photovoltaic modules with respect to safety and is to be used in conjunction of IEC 61215.

The PV modules covered by this standard are limited to a maximum DC system voltage of 1500 V.

2.1.2. IEC 61730-2

This part of IEC 61730 lists the tests a PV module is required to fulfill for safety qualification. IEC 61730-2 includes a general inspection and the following test categories: environmental stress, electrical shock hazard, fire hazard, and mechanical stress tests. Some specific tests in IEC 61730-2 include the following:

- Visual inspection;
- Performance at Standard Test Conditions (STC);
- Maximum power determination;
- Insulation thickness test;
- Durability of markings;
- Sharp edge test;
- Bypass diode functionality test;
- Accessibility test;
- Cut susceptibility test;
- Continuity test of equipotential bonding;
- Impulse voltage test;
- Insulation test
- Wet leakage current test;
- Temperature test;
- Hot-Spot endurance test;
- Fire test;

- Ignitability test;
- Bypass diode thermal test;
- Reverse current overload test;
- Module breakage test;
- Screw connections test;
- Static mechanical load test;
- Peel test;
- Lap shear strength test;
- Materials creep test;
- Robustness of terminations test;
- Thermal cycling test;
- Humidity freeze test;
- Damp heat test;
- UV test;
- Cold conditioning; and
- Dry heat conditioning;

The objective of IEC 61730-2 is to provide the testing sequence intended to verify the safety of PV modules whose construction has been assessed by IEC 61730-1. The test sequence and pass criteria are designed to detect the potential breakdown of internal and external components of PV modules that would result in fire, electric shock, and/or personal injury.

2.2. Qualification Testing

Qualification testing covers market requirements for commercial modules. We have identified the following international qualification testing standards to be relevant for perovskite PV module manufacturers:

- IEC/UL 61215-1 – Terrestrial photovoltaic (PV) modules – design qualification and type approval – Part 1: Test requirements
- IEC/UL 61215-2 – Terrestrial photovoltaic (PV) modules – design qualification and type approval – Part 2: Test procedures

IEC 61215 establishes the requirements for design qualification and approval of crystalline silicon PV modules. The objective of this standard is to determine the electrical and thermal characteristics of the module and to show, as far as is possible within reasonable constraints of cost and time, that the module is capable of withstanding prolonged exposure to different environmental conditions. The actual lifetime expectancy of modules will, however, depend on their design, maintenance, environmental conditions, and the actual weather conditions under which they are operated.

IEC 61215 includes tests that are designed to assess module reliability. Three of the most stringent tests included in IEC 61215 are the thermal cycling (TC) test, humidity freeze (HF) test and damp heat (DH).

Under the thermal cycling test, the modules are exposed to 200 cycles in which the temperature varies between -40 °C and +85 °C. The modules are tested for changes in physical properties. Under the humidity freeze test the modules are subjected to 10 temperature cycles from +85 °C (with 85 percent relative humidity) to -40 °C; and in the damp heat, the modules are held for 1000 hours at +85 °C (with 85 percent relative humidity) and observed for changes in physical and electrical properties.

Moisture penetration into the module is one of the potential failure modes that are exposed by these tests, especially the damp heat test. Moisture can eventually lead to module failure due to events such as the delamination of the backsheet, electrochemical corrosion of the solder joints and increase in the contact resistance at solder points and electrodes. Similarly, IEC 61215 includes tests to verify the resistance of the module to breakage under load or hail impact, robustness of the junction box, wires and connectors, among other potential failure modes. The IEC 61215 test sequence is detailed in Figure 2-1.

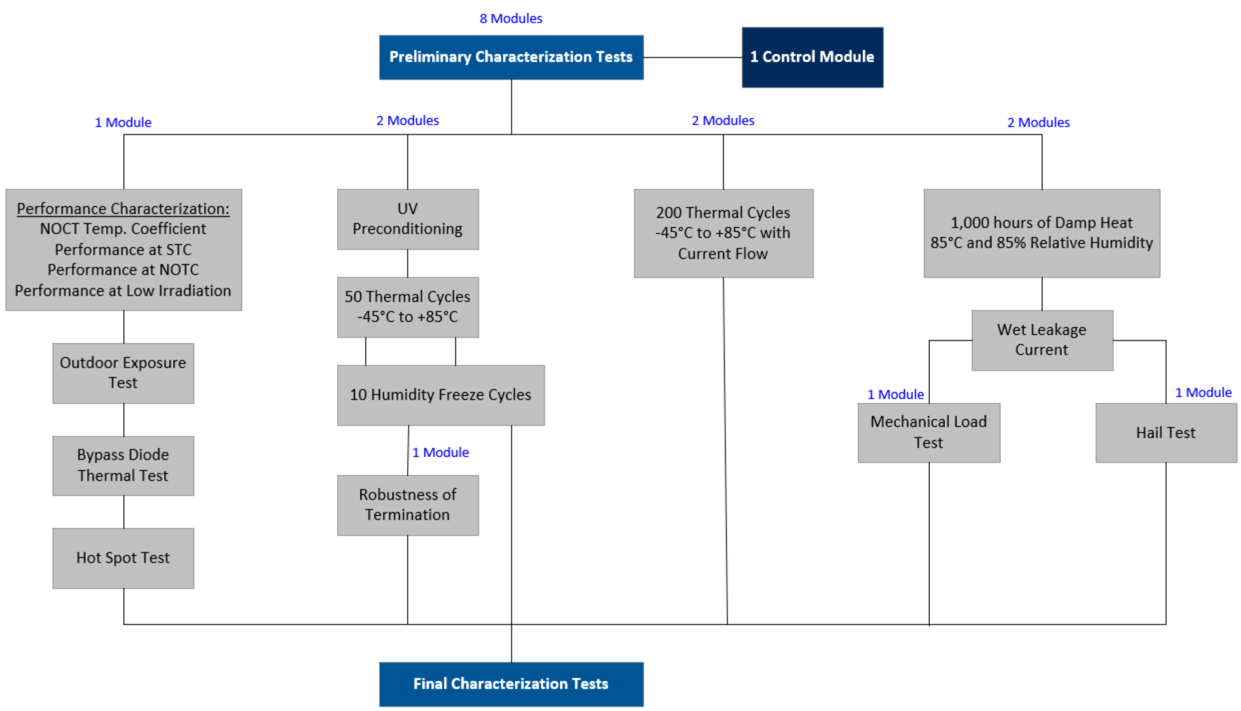

Figure 2-1. IEC 61215 Test Sequence

We believe that a module that successfully passes IEC 61215 testing has a higher likelihood of performing adequately in the field than a module that does not pass the tests.

We note that specific module technologies, such as, c-Si, CdTe, CIGS and amorphous silicon (a-Si) have annexes to IEC/UL 61215, referred to as 61215-1-X, that define the necessary modifications to the test protocols or specific parameters for each test and expects that annexes will be created to ensure appropriate testing of perovskite PV modules.

2.3. Extended Reliability Testing

PV module extended reliability testing is a market requirement for commercial modules in many commercial and industrial (C&I) and utility scale applications. In many cases the testing is performed according to custom third-party lab protocols and published standards including the following listed in Table 3-1 below.

Table 3-1. Extended Reliability Tests

Reliability Test	Scope
IEC TS 62804 – Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 1: Crystalline silicon standards	This standard does not currently apply to module/cell technologies other than c-Si. However, if perovskite PV modules suffer from potential induced degradation, parts of this standard may become more relevant.
IEC TS 62782 – Photovoltaic (PV) modules – Cyclic (dynamic) mechanical load testing standards	The module is supported at the design support points and a uniform load of 1,000 Pa ± 100 Pa normal to the module surface is cycled (3 to 7 cycles per minute) in alternating negative and positive directions. This test is performed to evaluate if components within the module including cells, interconnect ribbons and/or electrical bonds within the module are susceptible to breakage or if edge seals are likely to fail due to the mechanical stress.
IEC 62716 - Photovoltaic (PV) modules – Ammonia corrosion testing	Highly corrosive wet atmospheres, such as in the environment of agricultural applications, could eventually degrade some of the PV module components due to the absorption of ammonia (NH_3). This standard provides the means to evaluate possible faults caused in PV modules when operating under wet atmospheres having high concentration of dissolved ammonia. A test cycle subjects a PV module to an ammonia concentration of 6,667 ppm and relative humidity of 100% for 8 hours followed by reducing the ammonia concentration and relative humidity to 0 ppm and 75%, respectively, for 16 hours. 20 cycles are conducted and the degradation of the PV module is determined.
IEC 61701 - Photovoltaic (PV) modules – Salt mist corrosion testing	Highly corrosive wet atmospheres, such as locations near the ocean or wintery environments in which salt is used to melt ice formations, could eventually degrade some of the PV module

Reliability Test	Scope
	components due to the absorption of salts. This standard provides the means to evaluate the resistance of different PV modules to corrosion from salt mist containing Chlorine (Cl). Test procedures are conducted in accordance with IEC 60068-2-52 which contains eight different test methods with varying salt mist concentrations depending on the PV modules application.
IEC 60068-2-68 Lc2- Environmental testing - Part 2-68: Tests - Test L: Dust and sand	This part of IEC 60068 specifies test methods to determine the effects of dust and sand suspended in air, on PV module components. Dust and sand test parameters typically include a dust concentration of 5 g/m^3, sand type of 95% silicon dioxide, wind velocity of 20 m/s, and duration of four hours on both front and back side of the PV module.
IEC 63209 Photovoltaic (PV) modules – Extended-stress testing – Part 1: Modules and Part 2: Polymeric component materials	This standard provides information to supplement the baseline testing defined in IEC 61215. This standard provides a method for evaluating longer term reliability of PV modules and for different bills of material (BOM) that may be used when manufacturing those modules. This standard provides a framework for comparative qualitative analysis using stresses relevant to application exposures to target known failure modes.

We note that there are usually no pass/fail limits on module performance after reliability testing but typically a decrease of module maximum power (Pmp) of less than 5% on a particular test leg is desirable.

We note that it is unclear if standard approaches to PV module extended reliability testing will be appropriate for perovskite PV modules for several reasons:

- Standard approaches may not capture important perovskite PV degradation modes, e.g., degradation due to voltage bias under various conditions.
- Standard approaches may unfairly penalize perovskites and not allow for e.g., diurnal metastability recovery modes that occur outdoors but not in existing chamber testing, so protocols requiring intermittent illumination may need to be developed or refined.

3. REQUIREMENTS FOR PERFORMANCE CHARACTERIZATION

This section provides an overview of the performance characterization protocols for PV modules. Performance characteristic parameters are required for estimating energy yields from proposed PV systems. Performance model results are also a key input to the calculation of Levelized Cost of Electricity (LCOE) and other technoeconomic metrics by which new PV technologies are evaluated for investments. While there are a number of technical standards for measuring the performance of PV cells and modules, IEC 61853-1 & -2 cover the important measurements that are needed to model performance of a PV system in the field. Any serious customer interested in PV power production will require that these test results are available for PV modules they are considering to purchase.

There are important requirements that must be met before a module is ready for IEC 61853 testing. These are important to detail in the case of perovskite PV modules because this technology continues to have issues with metastable performance characteristics.

- A validated protocol must be defined for module preconditioning. The performance of most, if not all, PV technologies changes when exposed to ambient daylight conditions. Some of these changes occur when the modules are exposed to daylight for the first time and then generally remain stable afterwards (e.g., initial light soak preconditioning of c-Si modules). Other changes occur each time the module is exposed to daylight (e.g., morning) and revert back to the original state during the night. For these modules it is necessary to light soak for a given time prior to measuring performance so that repeatable results can be obtained in successive tests, regardless of the exposure history of the module. This is the case for many CdTe, CIS, and CIGS modules. Other modules (e.g., a-Si) experience seasonal changes in performance due to temperature changes over the seasons and/or changes in the solar insolation over longer periods of time. Any performance measurement requires confidence that the measurement is stable and repeatable, regardless of the exposure and/or storage history of the module. For new PV technologies, such as perovskites, preconditioning protocols need to be developed, tested, and validated.
- Performance characterization requires/assumes that modules do not degrade during the characterization test. A common way to ensure this is met for new technologies is to repeat the characterization tests multiple times to ensure that the results are consistent. If consecutive module characterization results vary this means that either the module has not been brought to a stable state for testing (inadequate preconditioning) or that the module is degrading during testing. In either case, performance characterization results are not reliable and should not be considered accurate.

3.1. IEC 61853-1

Part 1 of IEC 61853 defines a performance matrix of twenty-two irradiance & temperature conditions at which an IV curve is measured on the module.

Irradiance (W/m2)	Temperature			
	15°C	25°C	50°C	75°C
1100		⊕	⊕	⊕
1000	⊕	⊕	⊕	⊕
800	⊕	⊕	⊕	⊕
600	⊕	⊕	⊕	⊕
400	⊕	⊕	⊕	
200	⊕	⊕		
100	⊕	⊕		

⊕ Measurement condition specified in IEC 61853-1

Figure 3-1. IEC 61853-1 Matrix of Testing Conditions for IV Characterization of PV Modules.

3.2. IEC 61853-2

Part 2 of IEC 61853-2 provides measurement protocols for (1) measuring the effects of irradiance angle of incidence on the output power of the module, (2) determining the operating temperature of a module for a given set of ambient and mounting conditions and (3) measuring spectral responsivity of the module. These results provide parameters that are used in PV performance modeling, namely: incidence angle modifiers and spectral mismatch factors that are used to determine effective irradiance and coefficients used to determine a module's cell temperature from measured irradiance, ambient air temperature and wind speed.

4. SUMMARY AND CONCLUSIONS

In this report we have summarized the general set of quality, safety, reliability and performance testing standards that photovoltaic modules are currently required to pass in order that they may be sold and used in the United States. As perovskite PV technologies mature and improve, there may be a need to adjust some of these standards to allow for unique characteristics of perovskite PV materials and devices. At this time, such understanding has not yet reached a consensus and active research and development continues. The PACT center is actively working to build the technical basis for testing standards that fairly evaluate perovskite PV module technologies.

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