U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

# Performance Targets for Perovskite Photovoltaic Research, Development, and Demonstration Programs

## Request for Information Summary and Updated Metrics

February 2022

Solar Energy Technologies Office

# Introduction

On October 15, 2021, the U.S. Department of Energy Solar Energy Technologies Office (SETO) released the Performance Targets for Perovskite Photovoltaic Research, Development, and Demonstration Programs Request for Information (RFI) for public response and comment. The RFI sought feedback from industry, academia, research laboratories, government agencies, and other stakeholders on efficiency, stability and replicability performance targets for perovskite (PVSK) photovoltaic devices that could be utilized to align community efforts, ensure relevance of potential future funding programs, and accelerate technical and commercial development and de-risking of perovskite technologies. The RFI included the following proposed target matrix for power conversion efficiency (PCE), area, stability, and sample sizes, and included questions on relevance, completeness, and challenges.

**Original Performance Targets Matrix Proposal:**

| Configuration | Total Area PCE[1] | Total Module Area | Stability | Sample Population Requirements |
|---|---|---|---|---|
| Single Junction | 18% PCE | >=900 $cm^2$ | Pass IEC 61215 Module Quality Test (MQT) 10, 11, 12, 13, and 21 with <10% relative performance loss per test[2]<br><br>6 months continuous outdoor testing with <2% relative degradation | >1 kW total, at least 20 modules for outdoor testing[3] |
| PVSK-only Tandems | 25% PCE | | | |
| Hybrid Tandems | 27% PCE | | | |

1. Measured after at least 10 kWh/$m^2$ outdoor exposure
2. Validation Center (or other independent laboratory) will assign devices to each MQT from available sample population. Standard sampling protocols may not be followed due to available sample population sizes. Test overview:
   a. MQT 10 – UV preconditioning test: 15 kWh/$m^2$, 60°C
   b. MQT 11 – Thermal cycling test: 50 cycles, −40°C to +85°C
   c. MQT 12 – Humidity freeze test: 10 cycles from +85°C, 85% relative humidity (RH) to −40°C
   d. MQT 13 – Damp heat test: 1000 h at +85°C, 85% RH
   e. MQT 21 – Potential induced degradation test: IEC TS 62804-1 +85°C, 85% RH at maximum system voltage for 96 hours
3. Devices will be assigned to accelerated or outdoor testing by the Validation Center or other independent laboratory (not by the fabricator)

A total of 11 RFI responses were received and reviewed, including 6 from the perovskite and solar industry, 3 from national laboratory organizations, and 2 from academic institutions. This

document presents aggregated information from all RFI responses, a revised performance target matrix, and clarification on potential utilization by SETO.

### Revised Performance Target Matrix:

| Configuration | Aperture Area PCE[1] | Total Module Area[2] | Durability | Sample Population Requirements |
|---|---|---|---|---|
| Single Junction | 18% PCE | >=500 $cm^2$ with at least 4 interconnected cells | Pass IEC 61215 Module Quality Test (MQT) 10, 11, 13 and 21 and ISOS-L-2 at specified durations with <10% relative performance loss per test[3]<br><br>6 months continuous outdoor testing with <3% relative degradation overall and <1% degradation in the final 3-month span[4] | >1 kW total, at least 20 modules for outdoor testing[5] |
| PVSK-only Tandems | 24% PCE | | | |
| Hybrid Tandems | 27% PCE | | | |

1. Average of tested devices, measured after at least 10 $kWh/m^2$ outdoor or AM1.5 exposure (NOTE: this will be updated as the PACT Validation Center generates initial preconditioning test protocols)
2. Aperture/total module area > 75%
3. Validation Center (or other independent laboratory) will assign devices to each test from available sample population. Standard sampling protocols may not be followed due to available sample population sizes. Test overview:
    a. MQT 10 – UV preconditioning test: $15kWh/m^2$, 60°C
    b. MQT 11 – Thermal cycling test: 50 cycles, −40°C to +85°C
    c. MQT 13 – Damp heat test: 1000 h at +85°C, 85% RH
    d. MQT 21 – Potential induced degradation test: IEC TS 62804-1 +85°C, 85% RH at maximum system voltage for 96 hours
    e. ISOS-L-2 – Light-soaking: 1000 h, 1 sun AM1.5, +75°C, ambient environment
4. Conducted by the Validation Center; Averaged utilizing only on top-performing 90% of fielded devices (10% dropout acceptable)
5. Devices will be assigned to accelerated or outdoor testing by the Validation Center or other independent laboratory (not by the fabricator)

**Please note that unless explicitly stated, the U. S. Department of Energy (DOE) is not communicating an opinion or viewpoint about any of the responses described below, but rather is publishing an RFI response summary in addition to the revised targets so that the public may also benefit from information received by DOE.**

# Response Summaries

The RFI included four questions:

1. Do you feel all the proposed targets are relevant and necessary to proving technology performance of perovskite photovoltaic devices? If not, please specify why not.
2. What changes or additions, if any, would you make to the proposed performance targets to improve their relevance and usability?
3. Are there any specific tests, protocols, or targets that would be difficult for your organization to evaluate, require additional equipment, or place a large burden on your organization?
4. DOE is considering using these targets to evaluate applicant readiness for manufacturing RD&D programs – when do you anticipate your organization would be able to meet the targets as written?

Due to the responses received, which frequently provided interconnected responses to multiple questions, this summary will present feedback organized by target matrix section.

## General Responses

Overall, the respondents appeared supportive of the general concept of common performance targets for perovskite photovoltaics. However, three major alternatives were presented.

1. **Bifurcate targets:** There was some concern about the applicability of these targets, which align with the SETO priority area for low-cost, reliable electricity production, to alternative or initial markets. Similarly, there were concerns that some aspects of these targets might be too aggressive for academic or early-stage industrial groups. While details varied, there were multiple suggestions to establish two sets of performance targets--one for smaller devices that could be more applicable to academic R&D, earlier industrial development, and alternative markets, and one that would be applicable to a commercialization path to grid-tied electricity production.
2. **Wait to set targets:** There are many unresolved questions about the most relevant test protocols and performance requirements for perovskite photovoltaics. Suggestions were made that target finalization be deferred until more is known. The PACT Validation Center is tasked to address some of these questions and is in its initial year of operation.
3. **Eliminate targets:** Some groups indicated concern with setting any targets, as there are multiple markets and requirements can evolve rapidly. These groups suggested that SETO focus on directly funding projects to target any or all of these performance metrics, and to provide incentives or prizes for groups that show relevant progress.

Given SETO priorities and the preponderance of supportive responses, SETO intends to focus on optimizing a single target matrix and clarifying potential usage, which may resolve the concerns that resulted in the first alternative proposal. SETO also intends to revise this matrix as needed based on results from the PACT Validation Center and other community efforts.

Only a subset of responses addressed question #4 on time horizons, and these responses included a substantial range of timeframes under which these targets could be met as written. Groups indicated as short a horizon as one year, or as long as five years. Varying levels of corroborating and supporting information was provided for these estimates.

## Device Configurations

Respondents generally supported the three configurations proposed, but several suggested an addition: bifacial devices. No specific targets for bifacial devices were proposed, but respondents indicated that bifacial technologies are increasing in market share for incumbent technologies and are likely to be relevant to perovskites. The current target matrix does not exclude bifacial devices but does not set specific targets, in keeping with the goal of setting broadly applicable, general targets wherever possible

## Efficiency Targets

Feedback on PCE targets was mixed. Some groups supported increasing the targets, up to 22% PCE for single junction and 28% for hybrid tandems, while some supported decreases--primarily focusing on hybrid tandems, with proposed values around 23%. The proposed increases tended to be linked to proposals for smaller required device areas.

There were multiple questions about the use of "Total Area PCE", which was a concern given edge effects for non-optimized device fabrication. "Aperture Area PCE" was proposed as an alternative to resolve this issue.

There were also multiple responses questioning whether PCE was a sufficient metric for this target matrix. Energy yield was proposed as a more relevant metric--the argument made was that perovskites show evidence of a substantially lower temperature coefficient as compared to silicon or cadmium telluride technologies. This means that modules with identical PCEs as measured at standard testing conditions might have quite different effective operational PCEs, as modules tend to operate at significantly higher temperatures than test conditions. The respondents indicated that a lower standard PCE for perovskites might be acceptable, as operational energy yield could still exceed incumbent technologies.

## Area Targets

In general, respondents indicated interest in reduced module area requirements, though some indicated support for the proposed value. The alternative proposed sizes were as small as 100 $cm^2$, but the most common proposal was for 225 $cm^2$, which would align with a standard 150 mm by 150 mm platform, similar to silicon solar cells. The rationales for the proposed reductions centered around equipment availability and throughput. Some groups indicated that this size was not on their current scaling roadmap and would therefore impose an additional burden to acquire relevant tooling. Multiple groups indicated that the metallization steps were the primary concern, with either a lack of capability to support the proposed size, or a throughput issue that would cause resource balancing challenges.

Additionally, there were some concerns about relevance of the size for the alternative and initial markets as described in the "General Responses" section. Groups that proposed size reductions also frequently indicated a willingness to increase overall device count requirements or include process yield targets.

## Stability Targets and Testing Protocols

Respondents generally supported a subset of the proposed testing protocols. There were concerns with the ability of each entity to conduct the full range of testing. Additionally, it was proposed to change the title to "Durability" or "Reliability" rather than "Stability."

### Preconditioning

Groups indicated a lack of confidence that the proposed presoak was sufficient and relevant. Multiple suggestions around asymptotic output requirements and similar requirements were made, as well as proposals to defer defining this protocol pending initial PACT recommendations on this topic.

### Accelerated Testing

A general, repeated suggestion was to reduce the number of tests as much as possible to minimize burden. Given the current state of perovskite technologies, groups felt that tests directly targeting acceleration of device failure modes (mainly light, heat, cycling, and bias) were more immediately relevant than tests that initially exercise the package itself (humidity, etc.). Suggestions were made to include light soaking at elevated temperature, similar to International Summit on Organic Photovoltaic Stability (ISOS) protocols, and to expand the reverse bias/partial shading testing.

### Outdoor Testing

Responses to the outdoor testing proposal varied--some groups supported extending the requirement to a full year at minimum, to ensure that annual variability was captured, as well as requiring multiple sites to capture climatic variability. Other groups indicated that the test duration was too long relative to their innovation cycles. There were also concerns about the success value

proposed, primarily due to potential burn-in or similar behaviors that might lead to a larger initial drop, followed by more stable behavior.

## Revised Target Matrix

Following the RFI, SETO reviewed the responses in detail and revised the proposed performance target matrix. The final matrix can be found below. Significant changes include:

- Revision of PCE definitions and perovskite tandem target values.
- Revision of area requirements to reduce burden while maintaining interconnection requirements.
- Revision of test protocols to focus on device stressors vs. packaging and clarify outdoor performance targets.

Some recommendations were not adopted, due to a variety of reasons, including but not limited to lack of alignment with SETO priorities and market requirements, lack of ability to set clear targets and rapidly assess performance around proposed alternative metrics, or lack of agreement across a plurality of responses.

**Revised Performance Target Matrix:**

| Configuration | Aperture Area PCE[1] | Total Module Area[2] | Durability | Sample Population Requirements |
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5. Devices will be assigned to accelerated or outdoor testing by the Validation Center or other independent laboratory (not by the fabricator)

## Clarification on Potential Utilization within Research, Development, Demonstration, and Commercialization Programs

Given the responses received, SETO believes there is value in clarifying the intent and potential utilization of this performance target matrix.

As stated in the RFI, perovskite photovoltaic technologies show the potential for high-efficiency operation and low production costs. As such, they may significantly contribute to achieving SETO's goals for low-cost domestic solar electricity. The research and development community has demonstrated high-performance devices at small device area and operational scale, as well as the applicability of high-throughput manufacturing approaches, such as roll-to-roll fabrication. For commercial success, perovskite technologies must simultaneously achieve high performance, high stability, low cost, and verifiable performance. The latter includes the ability to pass IEC design qualification and type approval certification, safety qualification, as well as performance testing and energy rating applicable to all PV technologies. These internationally agreed upon test protocols are based on decades of experience of PV module deployment as well as horizontal standards governing energy generating equipment. Even though the current matrix of targets does not include key accelerated stress test sequences (AST) SETO reiterates that early focus on meeting market requirements is pivotal to the success of the technology.

The breadth and diverse composition of the perovskite community necessitates programs that target a variety of objectives. Prior funding programs illustrate this, with the SETO Perovskite FOA including both device R&D (Topic Area 1) with lower cost share requirements focused on earlier stage academic and national laboratory investigations, and manufacturing R&D (Topic Area 2) with increased cost share requirements and suggestions for some performance levels that may be required. Similarly, the Fiscal Year 2021 Incubator FOA included a similar progression for businesses and product development, with Topic Areas that progressively increased in overall funding level and requirements.

These FOAs were targeting projects at specific phases within the research, development, demonstration, and commercialization continuum. It is likely that SETO will continue to run programs targeting these phases for a range of solar generation and integration technologies, and unlikely that SETO would attempt to apply highly defined requirements or targets to similar programs in the future.

While SETO cannot commit to any future funding programs, the performance target matrix is a potential option to help establish confidence and manage risk for different types of programs which target manufacturing and commercialization challenges on larger scales and funding levels than these prior programs.

In closing, SETO would like to thank the community members for their thoughtful and detailed responses to this RFI. Continued community engagement and collaboration is key to fully understanding the challenges and opportunities presented by perovskite technologies.

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DOE/EE-2564 • February 2022