U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Photovoltaics Innovation Roadmap Request for Information Summary

Solar Energy Technologies Office

January 2018

Introduction

On June 28, 2017, the U.S. Department of Energy's Solar Energy Technologies Office (SETO) released the *Photovoltaics (PV) Innovation Roadmap Request for Information (RFI)* for public response and comment. The RFI sought feedback from PV stakeholders, including research and commercial communities, about the most important research and development (R&D) pathways to improve PV cell and module technology to reach the SETO's SunShot 2030 cost targets of $0.03/W for utility PV installations, $0.04/W for commercial scale installations, and $0.05/W for residential PV installations. Early-stage scientific and technological innovation that increases cell or module efficiency, maximizes annual energy production, decreases costs, and improves system durability and grid reliability is critical to continue to lower the costs of solar electricity and support greater energy affordability. To solicit feedback about these major PV technical challenges, the RFI asked questions covering four sections (please refer to the RFI for further background on each topic):

1. Technological Research Priorities;
2. Characterization and Modeling Techniques;
3. Module Packaging and Reliability; and
4. Portfolio Evaluation.

A total of 89 RFI responses were received, including 37 from industrial companies or consultants, 28 from universities, 22 from national laboratories, one from a non-profit organization, and one from another government agency. This document presents aggregated information from all RFI responses, organized by the sections above. **Please note that the Department of Energy (DOE) is not communicating an opinion or particular viewpoint about any of the responses described below, but rather publishing a RFI response summary so that the public may also benefit from the information received by DOE.**

1 Technological Research Priorities

1.1 a) Do you believe organizing R&D projects by functional areas spanning specific technologies could promote innovation and collaboration? Why or why not?

A majority of responses expressed some interest in exploring how a subset of SETO funding could be directed to R&D projects targeting PV functional areas that span absorber technologies. Most respondents focused their response on specific insights regarding how such a funding structure could succeed or fail. The table below summarizes responses about potential research areas where a functional approach could be successful as well as potential challenges to this type of organization.

Table 1. List of potential research areas and potential challenges for R&D efforts that focus on PV functional areas spanning absorber technologies

Potential Research Areas	Characterization
	Reliability and durability
	Metallization
	Contacts
	Surface passivation
	Interfaces and grain boundaries
	Conductive inks/adhesives
	Technologies beyond the cell
Potential Challenges	Problems and relevant solutions are too unique to a specific absorber technology
	Requires strong, high-level leadership to synergize multiple areas of expertise
	Projects might fail if targeting too broad of a research topic
	Growth and/or crystallization methods are not effective areas for this type of focus
	Knowledge may not transfer easily across areas of expertise
	Dilutes core expertise needed for high-performing baseline within an absorber technology
	Requires evaluation to understand benefit

b) We are interested in input about the most important technical challenges to improving cost, reliability, and efficiency within your area of PV expertise and how these could be categorized into important functional areas. Please provide technology-specific examples (at the supply chain, cell, module, or system level), along with associated technical challenges, quantitative cost/performance targets, and proposed functional areas.

Respondents provided over 200 technology-specific examples of challenges, each associated with quantitative metrics and a proposed functional area. In order to systematically aggregate these responses to examine trends across responses, text analyses were conducted to create a DOE-defined list of categories for technologies, challenges, and functional areas that were then assigned to each submitted example. Table 2 lists the final categories used to aggregate results from this question. Please note that this list is not meant to encompass all possible categories relevant to the PV industry but rather captures the scope of responses provided in the RFI. Some categories have the potential to overlap (e.g. the 'potential-induced degradation' and 'degradation rate' challenges), since these categories have been determined based on the specificity and content of each respondent's example. Only one technology, challenge, and functional area tag has been applied to each example.

Table 2. List of DOE-assigned Technology, Challenge, and Functional Area categories assigned to each technical challenge submitted to Question 1.1.b

Technology	Challenge	Functional Area
BOS	Absorption	Absorber
BOS - Bypass Diodes	Carrier lifetime	Architecture
BOS - Power Electronics	Characterization	Cell-to-Module Conversion
Cell	Charge extraction	Collaboration
Cell - CdTe	Cost	Contacts
Cell - CIGS	Cracking	Defects
Cell - Coating	Degradation rate	Doping
Cell - Concentrator	Efficiency	Environmental Impact
Cell - DSSC	Failure understanding	Financing
Cell - Earth-Abundant	Fill factor	Frame and Racking
Cell - III-V	Financial understanding	Grid Integration
Cell - II-VI	High-voltage stress	Installation
Cell - Perovskite	Light stress	Interconnection
Cell - Power Electronics	Material use	Interfaces
Cell - Silicon	Moisture ingress	Manufacturing
Cell - Thin Films	Open-circuit voltage	Module Packaging
Cell - TPV	Optical losses	Optical Design
Cell - Transparent Conductor	Organization	Reliability and Durability
Module	Potential-induced degradation	Surface Passivation
Module - Adhesive	Predictive modeling	System Design
Module - Backsheet	Scientific understanding	Wafer and Cell Preparation
Module - Bifacial	Shading	
Module - CIGS	Standardization	
Module - Coating	Thermal losses	
Module - Encapsulant	Thermal management	
Module - Frame	Toxicity	
Module - Glass	Uniformity	
Module - Metallization	Valuation	
Module - Silicon		
System		
System – BIPV		

The full set of examples submitted to the RFI, along with DOE-assigned Technology, Challenge, and Functional Area categories, are reported in a separate ***RFI Technical Challenges*** Excel spreadsheet posted to the SETO website. The spreadsheet contains full responses that provide more detail for each of the technical challenges binned by category (e.g. Cost, Optical Losses, etc.). Below are several graphs produced using this data that highlight the technical challenges (listed along the x-axis) reported for some of the most frequently reported Technology and Functional Area categories. Figure 1 organizes results by cell or module technology, whereas Figure 2 reports results by functional area. Similar graphs can be created using the data found in the ***RFI Technical Challenges*** spreadsheet.

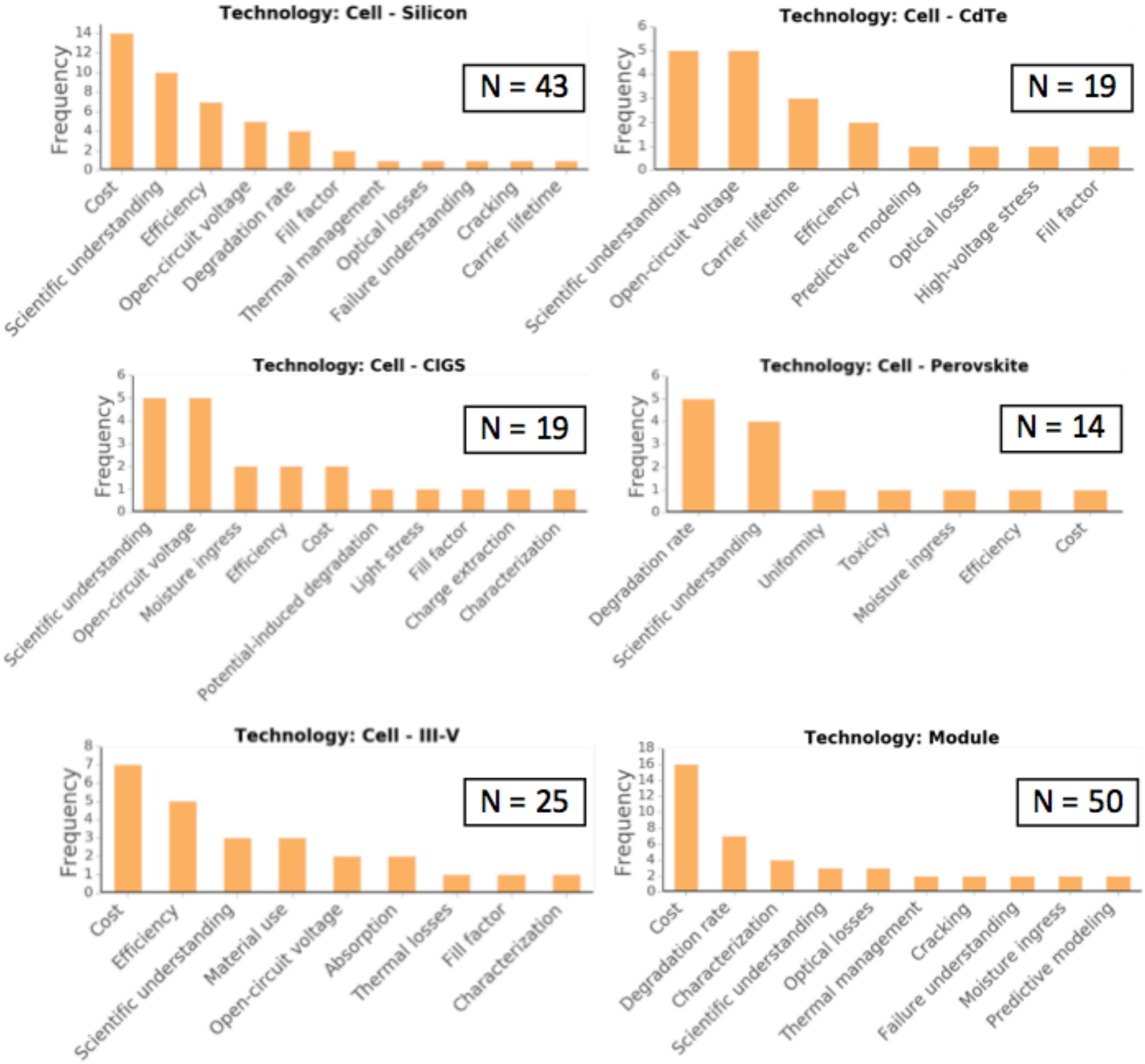

Figure 1. Technical challenges (listed along x-axis) categorized by DOE-assigned Technology categories based on RFI responses to Question 1.1b. Challenge and Technology categories were assigned using the lists shown in Table 2. The value of N in each subfigure corresponds to the total number of examples provided in that category.

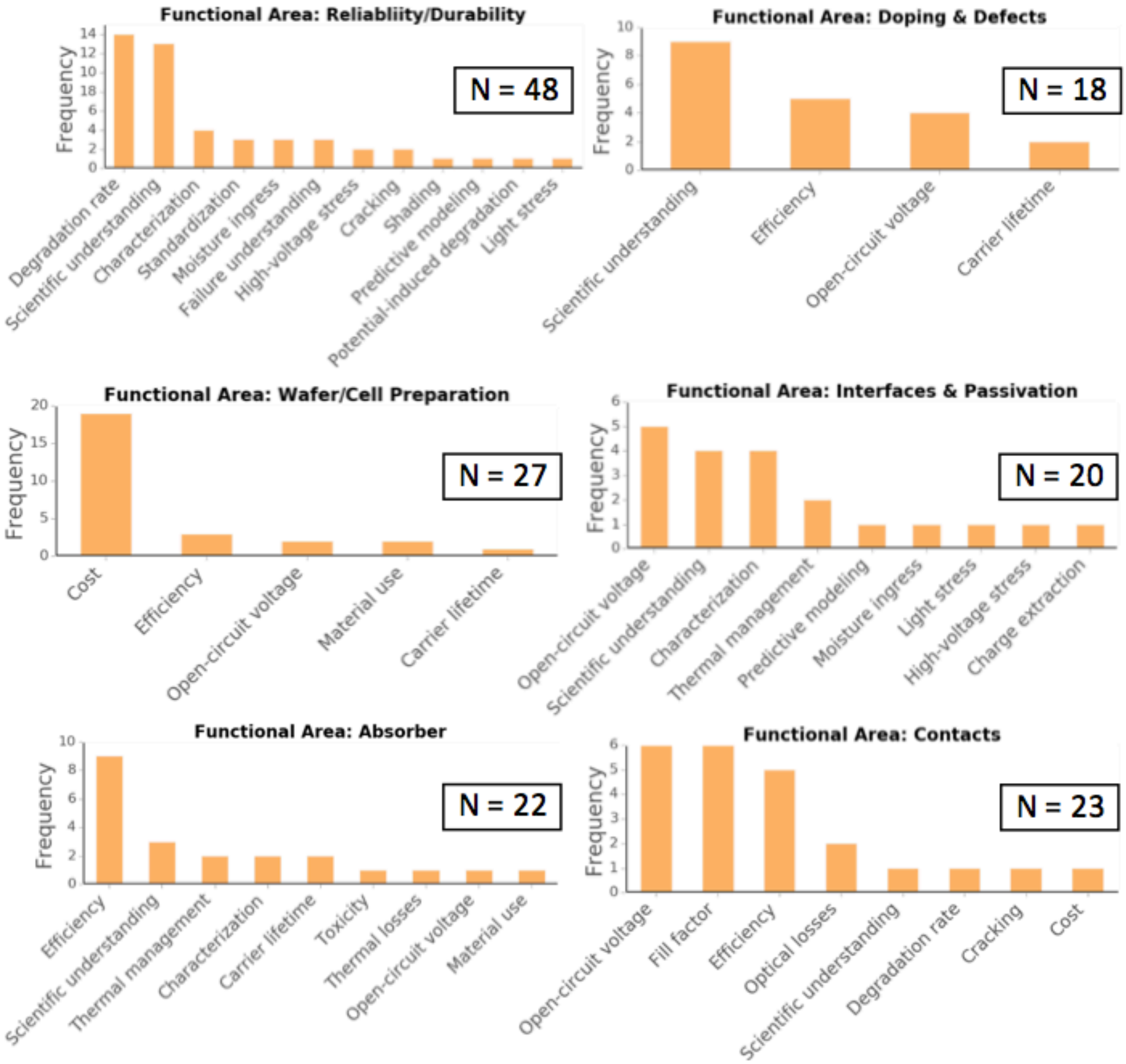

Figure 2. Technical challenges (listed along x-axis) categorized by DOE-assigned Functional Area categories based on responses to Question 1.1b. Challenge and Functional categories were assigned using lists shown in Table 2. The value of N in each subfigure corresponds to the total number of examples provided in that category.

1.2 We are interested in the PV community's perspective about the potential for various long-term technology innovations to address cost barriers related to efficiency, reliability, annual energy production or degradation, supply chain/capex costs, manufacturing costs, and grid resiliency or reliability. Please indicate the likelihood that each technology below will improve at least one important performance or cost characteristic (e.g., open-circuit voltage, short-circuit current, fill factor, degradation rate, supply chain/capex costs, module lifetime), without negatively affecting performance or cost in other areas so that it could meet SunShot 2030 cost targets.

This question provided a table of technologies spanning cell, module, supply chain, and grid reliability categories (refer to the RFI for full table), and asked respondents to assign a percent likelihood that each technology would address cost barriers by 2030, as described above. The graphs below report descriptive statistics (i.e. mean and standard error) of responses for each technology categorized by university, industry, and national laboratory (NL) respondents. In general, each category includes 30 to 40 responses. Figure 3 reports aggregated results for cell technologies. Figures 4, 5, and 6 report similarly categorized results for module, supply chain/capex, and grid-related technologies, respectively.

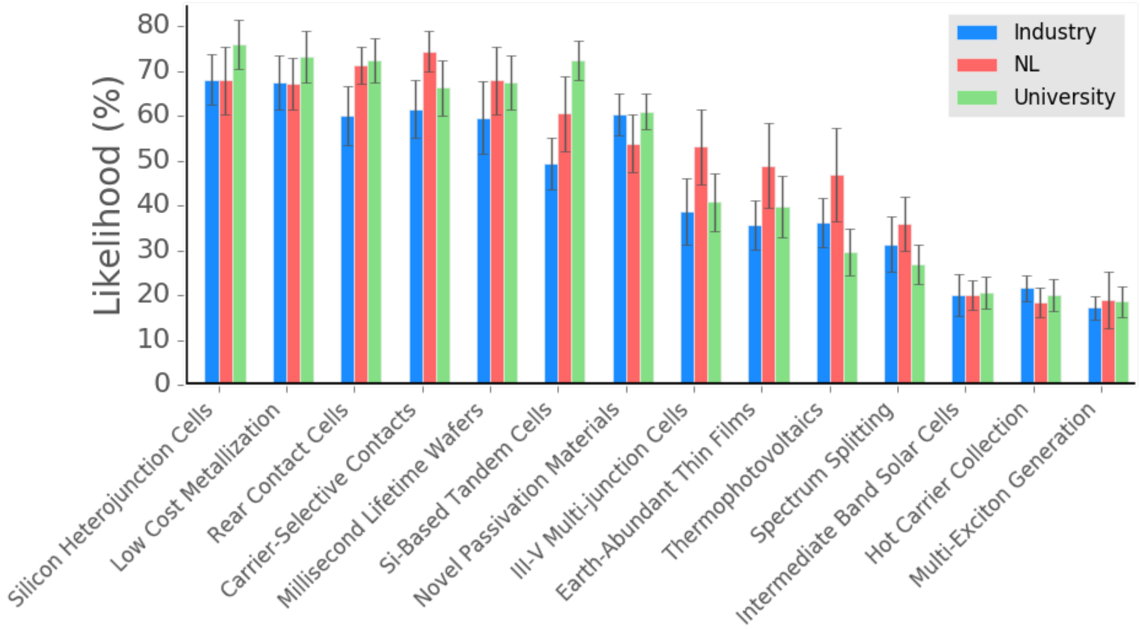

Figure 3. The mean and standard error of all RFI responses rating the likelihood of cell technologies to improve performance or cost characteristics while meeting SunShot 2030 cost targets.

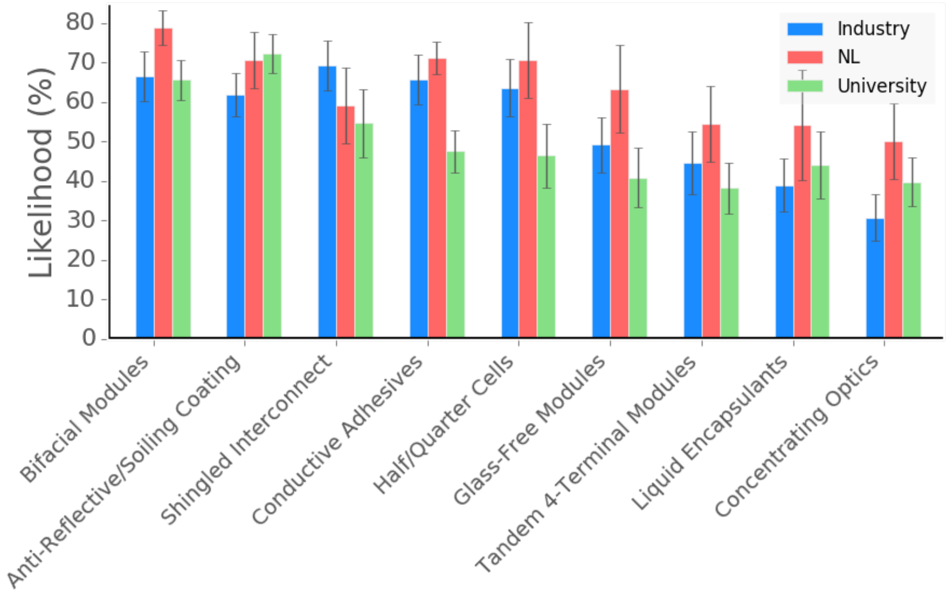

Figure 4. The mean and standard error of all RFI responses rating the likelihood of module technologies to improve performance or cost characteristics while meeting SunShot 2030 cost targets.

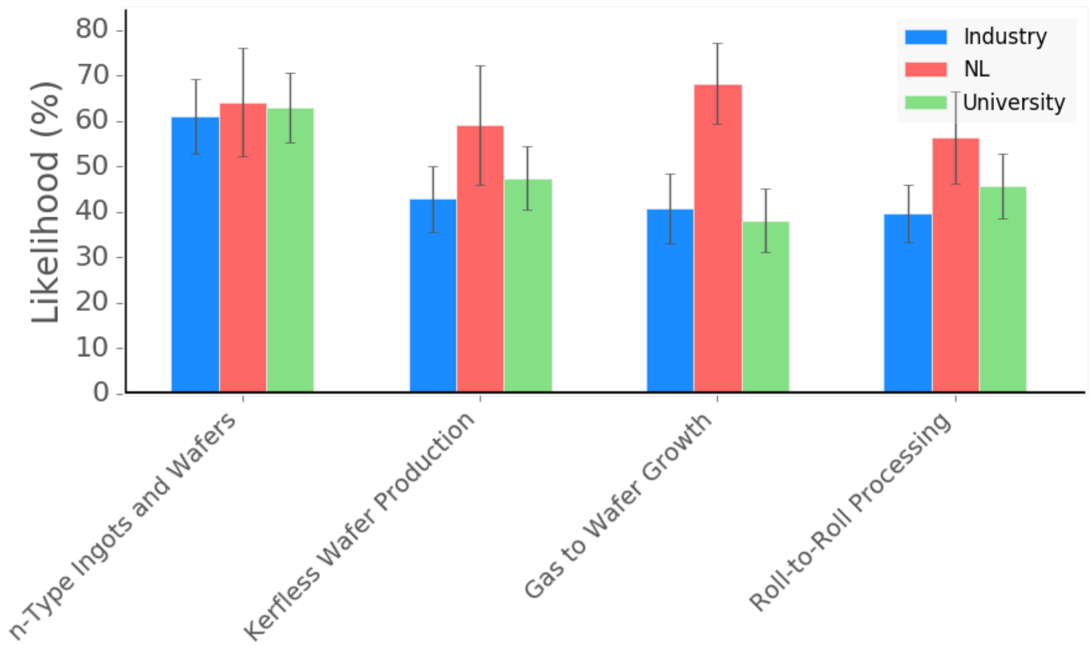

Figure 5. The mean and standard error of all RFI responses rating the likelihood of supply chain/capex technologies to improve performance or cost characteristics while meeting SunShot 2030 cost targets.

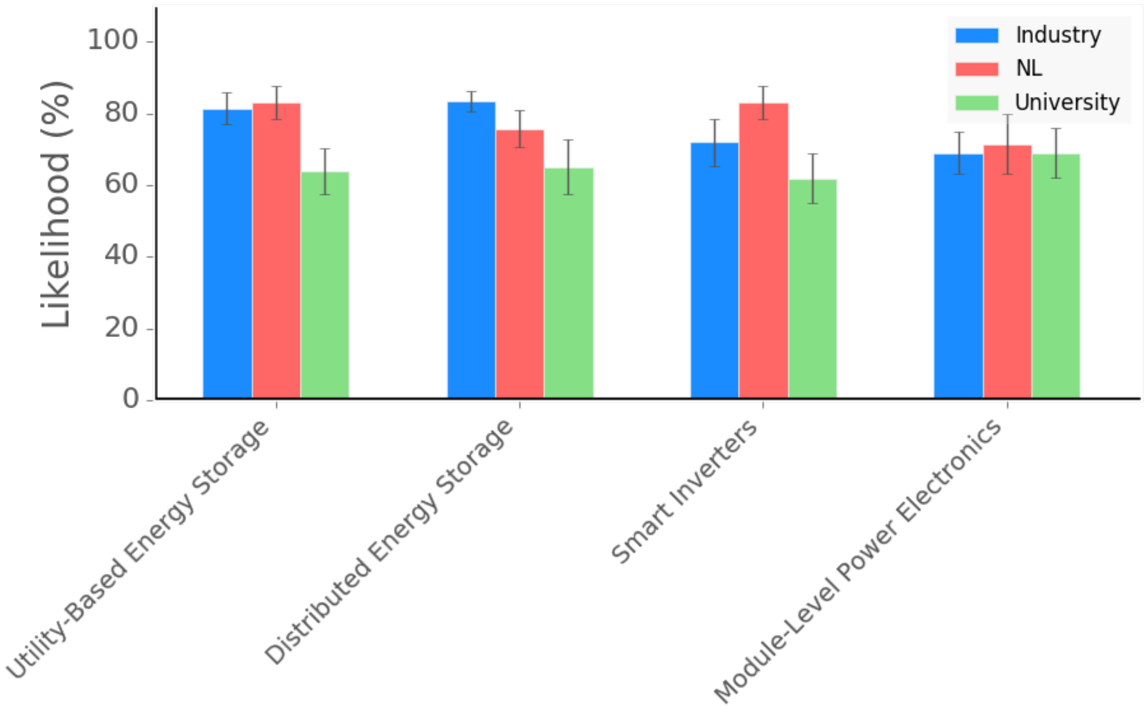

Figure 6. The mean and standard error of all RFI responses rating the likelihood of grid-related technologies to improve performance or cost characteristics while meeting SunShot 2030 cost targets.

1.3 What are the most important properties of cell-level research and development projects to ensure results that are meaningful at the module and system levels?

All responses to this question were categorized into manually determined topics that addressed how cell-level research can be meaningful at module and system levels. Figure 7 shows the percent of responses that addressed each topic.

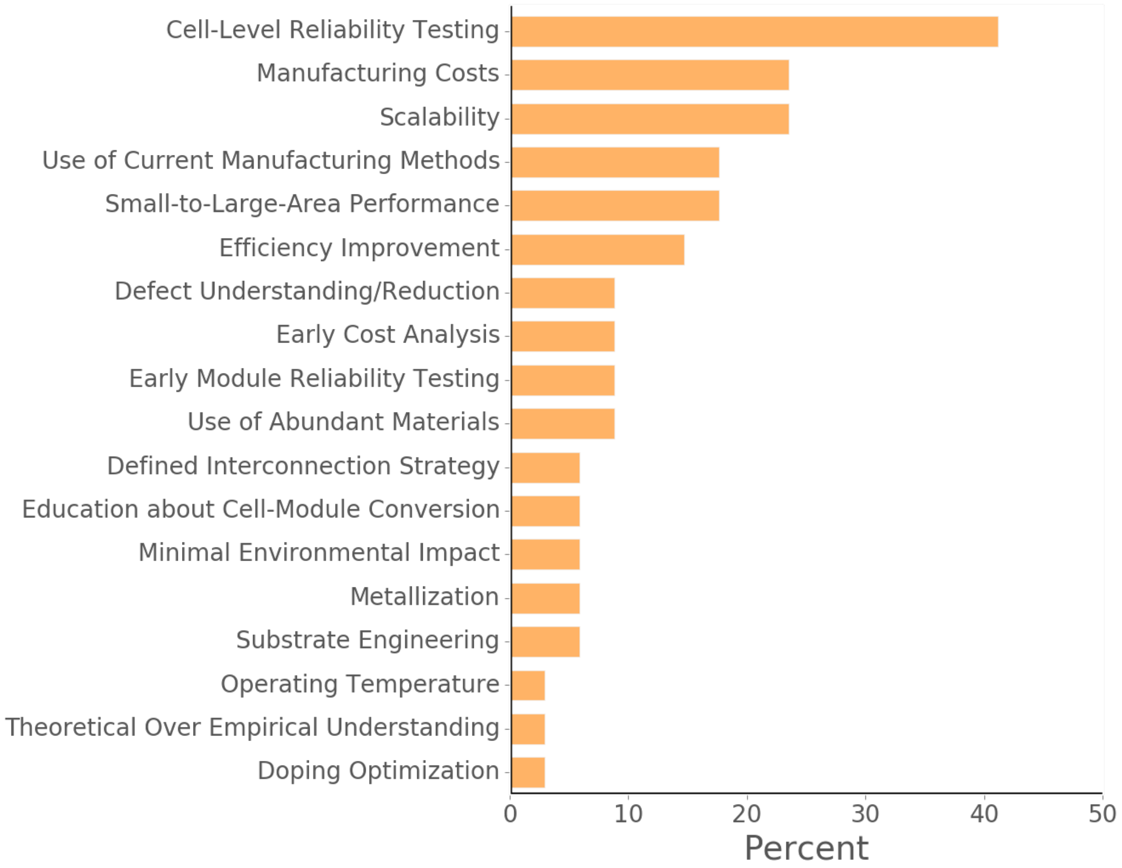

Figure 7. Percent of respondents addressing each of the categories listed on the left-hand side of the figure that relate to properties of cell-level R&D that impact module-level performance.

1.4 How can advances in PV research and development address electrical grid resiliency and reliability?

Responses to Question 1.4 addressed both PV-specific R&D priorities for grid resiliency and reliability as well as technologies beyond the PV module, such as storage, microgrids, and market structure. Due to the limited number of responses (29) to this question, we have listed general response categories in Table 3 rather than plotted responses by frequency, with the categories listed by frequency in descending order.

Table 3. Research and development priorities to address grid resiliency and reliability in descending order of frequency reported. The left-hand column lists R&D priorities related to PV cells and modules, whereas the right-hand column reports R&D efforts to address grid resiliency beyond the module.

R&D Priorities for Grid Resiliency Cells and Modules
Cell-level data acquisition
Reduced levelized cost of electricity allowing for fast ramping or curtailment as alternative to storage
Module form factors for disaster response and harsh environments
Data analytics for PV plant health beyond power performance output
Cell or module technology that reduces generation variability (e.g. low-light conversion)
Built-in, module-level energy storage
Maintenance scheduling and module failure detection
Thermophotovoltaics for energy storage
Bifacial modules for high latitudes
Simulations of how cell-level improvements can affect module design and system optimization

R&D Priorities for Grid Resiliency Beyond PV Modules
General energy storage
Irradiance forecasting
Smart power electronics
Battery storage
Demand response
Electric vehicle charging
New rate structures
Capacitive storage
High-voltage DC power optimization
Utility education about effects of long-term PV deployment on grid
Microgrids
Load optimization
Microinverters
Cybersecurity
System design and topology to better match generation to load
Grid topology

2 Characterization and Modeling Techniques

2.1 What are the key technical challenges that could be better understood and/or solved with improved characterization or modeling techniques in order to meet SunShot 2020 and 2030 cost targets?

Table 4 lists all technical challenges provided in RFI responses, organized by technology level (i.e., cell, module, system) and absorber technology if applicable. The Challenge column provides a brief description of the challenge described in each individual response. In addition to technical challenges, a majority of responses included potential types of characterization techniques that are also included in the challenge descriptions in Table 4. The table is organized by cell, module, and system level challenges.

Table 4. List of technical challenges to address and/or characterization and modeling techniques included in RFI responses to Question 2.1.

Level	Absorber	Challenge
Cell	CdTe	Characterizing point defects in bulk and at surfaces over spatial and energy distributions
Cell	CdTe	Models describing chemistry of CdCl2 annealing process and connection to performance
Cell	CIGS	Synthesis of characterization data at different length scales to understand metastabilities and process-property connection
Cell	CIGS	Measuring defects in a way such that results can be input into device models to predict cell performance
Cell	CIGS	Measurements of vacancy concentrations to understand how they affect metastability and performance
Cell	CIGS	Interpretation of capacitance measurement techniques to elicit more information about doping and defects
Cell	CIGS	Measuring buffer layer doping when part of entire device stack
Cell	CIGS	Understanding impact of 2D non-uniformities using device models
Cell	Thin Film	Characterizing active and inactive dopants beyond use of SIMS and CV/Hall
Cell	Thin Film	Physical understanding of reducing recombination at grain boundaries
Cell	Thin Film	Understanding metastabilities (e.g. light-induced) and related degradation
Cell	Thin Film	Understanding mechanisms driving metastabilities under light or heat stress and in different growth conditions
Cell	Thin Film	Developing transient spectroscopies and diffraction methods that are sensitive to trap states and can characterize local structure around them
Cell	Thin Film	Developing operando characterization techniques to understand how defects evolve during cell operation under light and voltage bias
Cell	Concentrating PV	Characterizing quantum efficiency at high intensity to test photocurrent linearity assumption
Cell	Multijunction	Evaluating recombination velocities and lifetimes in individual junctions
Cell	Multijunction	Determining internal radiative efficiency for each multijunction layer
Cell	Silicon	Understanding fast diffusers in silicon, such as whether H passivating B-O complexes provides good long-term performance, and whether Cu or Ni can be gettered by Al2O3 field
Cell	Silicon	Understanding degradation mechanisms in advanced silicon architectures
Cell	Silicon	Characterizing and modeling defects in Si ingots
Cell	Silicon	Improving diamond wire monitoring and wear modeling
Cell	Silicon	Improving substrate modeling for design of millisecond lifetime wafers
Cell	Silicon	Decoupling the impact of contact resistance and emitter surface concentration in predicting device performance
Cell	Silicon	Understanding how non-uniform dislocation densities in Si metamorphic cells affect performance
Cell	Multiple	Separating resistive loss contributions by stack layer to inform design

Cell	Multiple	Comprehensive defect characterization that requires multiple techniques and models to converge on understanding
Cell	Multiple	Developing 2D and 3D semiconductor models at the diode (micron) scale
Cell	Multiple	Implementing fast characterization techniques at scale to become routine process improvement tools
Cell	Multiple	Modeling defects using advanced electronic structure methods and exascale computing
Cell	Multiple	Understanding interfaces and passivation using electronic structure and molecular modeling
Cell	Multiple	Understanding how microscopic defects connect to cell-level performance using operando characterization and atomic modeling
Cell	Multiple	Rapidly characterizing fabricated devices for timely design feedback
Cell	Multiple	Physical understanding of device performance via multi-scale models that connect first-principles calculations to continuum-scale device models
Cell	Multiple	Developing multi-scale characterization to understand how bulk and interfacial defects affect optoelectronic properties and degradation
Cell	Multiple	Understanding of defects and surface states
Cell	Multiple	Developing fast and reliable methods to measure the chemical and electrical properties of grain boundaries
Cell	Multiple	Developing 2D and 3D device models
Cell	Multiple	Understanding structural and electronic properties of interfaces to reduce non-radiative recombination
Cell	Multiple	Open-access, standardized device models for cell technology beyond silicon
General	Multiple	Extending device physics knowledge from cells to modules and systems to provide feedback from fielded modules to cell design
General	Multiple	High-throughput evaluation approaches using open-access databases
General	Multiple	Disseminating knowledge among industry about all characterization techniques available and improving coordination required to leverage these techniques
General	Multiple	Improving indoor solar simulators to better match to outdoor experiments and measurements
General	Multiple	Developing novel characterization techniques beyond the standard set traditionally used in PV research and development
Module	Coating	Improving optical models for anti-reflective coating design
Module	Multiple	Developing low-cost cell characterization in modules to detect cell-cell variation in fielded modules, especially important for thin film technologies with monolithic manufacturing
Module	Multiple	Identifying unique, component-level accelerated failure mechanisms across a module stack and determining how they combine into a predicted module lifetime
Module	Multiple	Physics-based device modeling to inform predictive degradation tests
Module	Multiple	Electro-thermal modeling of cells and modules
Module	Multiple	Leakage current modeling to predict high-voltage reliability issues
Module	Multiple	Modeling of moisture ingress in various climates to understand corrosion
Module	Multiple	Understanding effect of UV and moisture exposure on degradation rate for new module components
Module	Multiple	Developing multi-scale and multi-technique analyses to connect module performance to microscopic origins

Module	Multiple	Understanding thermal and mechanical degradation processes using finite element analysis
Module	Multiple	Faster accelerated testing to allow for rapid material evaluation
Module	Multiple	Characterizing cell performance in modules
Module	Multiple	Correlating real-world degradation rates to results from laboratory or accelerated testing for a variety of module designs
Module	Multiple	Improving characterization and modeling to assess stress and strain, contaminant diffusion, and light-induced effects
Module	Silicon	Understanding of interface chemistry to address corrosion, adhesion, species diffusion, LID, PID
System	BIPV	Developing accurate economic analysis of architectural solar (e.g. BIPV) since its valuation is more complex than traditional LCOE
System	Multiple	Integrating system and component data into performance prediction models
System	Multiple	Predicting fielded performance with thermal and electrical changes
System	Multiple	Ray optics modeling to optimize system design
System	Multiple	Improving energy prediction models to reduce production uncertainty
System	Multiple	Developing models using spectral plane-of-array solar data from satellites
System	Multiple	Improving forecasting models and higher spatial and temporal resolution to support higher penetration of PV onto electrical grid
System	Multiple	Improving cost and accuracy of PV system performance prediction models to reduce financial risk
System	Multiple	Improving system-level data collection to allow for root-cause analysis of plant performance and reliability
System	Multiple	Modeling system performance while accounting for annually changing parameters and system configuration
System	Multiple	Developing tools for small installers to optimize residential system design
System	Module	Quantifying financial risk related to each type of cell or module defect using Risk Priority Numbers (RPNs)

2.2 What characterization or computational modeling techniques have been developed but not yet applied to PV research and development that could be useful to study materials, cells, and/or modules to improve efficiency or reliability?

Respondents provided examples of characterization and modeling techniques that have not been applied to or are underutilized in PV R&D. Figure 8 summarizes the general categories of techniques mentioned across all responses. Table 5 provides short descriptions of some of the underutilized technologies recommended and a brief summary of how they could be applied to PV research.

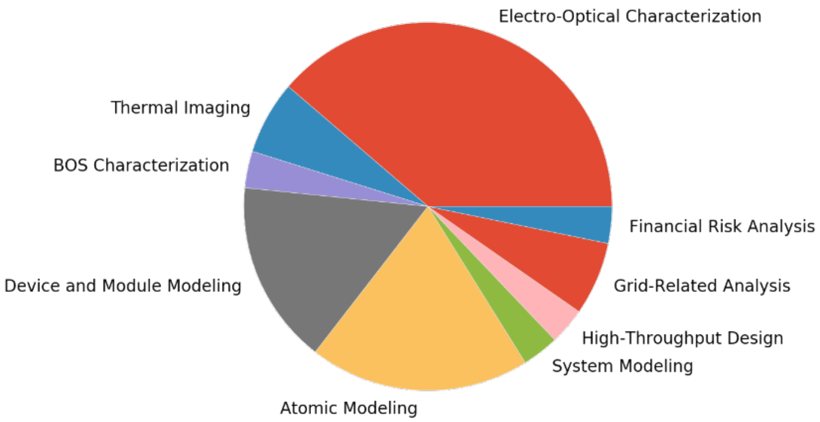

Figure 8. Categories of all proposed characterization or computational techniques included in responses to Question 2.2. Note that an individual RFI response could include content applying to more than one category shown above.

Table 5. List of characterization or modeling techniques underutilized in or not applied to PV research and development based on responses to Question 2.2.

Technique	Description
Statistical analysis techniques commonly applied in manufacturing process controls	Use software similar to JMP to analyze grid stability, energy usage, storage, and economic optimization.
Photoluminescence Excitation Spectroscopy	Measure radiative recombination in open-circuit to study surface and bulk effects
High-throughput modeling and experiments	Tailor material discovery to PV properties
Two-photon excitation microscopy	Apply to device characterization and design
Electric-field-induced second harmonics	Apply to device characterization and design
Time-resolved emission spectroscopy	Apply to device characterization and design
Computational actuarial science methods	Compile and analyze statistical data from lab and field stress studies to quantify financial risk
Micro- and nanoscale heat transport imaging	Identify highly localized heating connected to degradation
In-situ beamlines and synchrotrons	Study processing methods and surface passivation
Femtosecond spectroscopies taken from OPV	Apply to charge-transport and defect studies
Magnetic resonance techniques	Relate local chemical variations to lifetime, applied to silicon degradation or thin film characterization
Proper Orthogonal Decomposition method	Improve accuracy of electronic structure calculations
Large-scale (>1000 atoms) band-gap-corrected density functional theory (DFT) calculations	Study realistic defect concentrations and heterostructures
DFT modeling of interfaces and defects	Improve accuracy of ab initio models

Electron holography using transmission electron microscope (TEM)	Image electric field in cross-section for p-n junctions to understand recombination and doping
Thermal/mechanical modeling of harmonics expansion coefficients and material fatigue	Understand material durability
Dark/light lock-in thermography	Examine solder bond degradation and fill factor loss
Finite element analysis on modules and cells	Understand material durability
2D/3D device models developed at universities	Transfer university knowledge to industry
Sub-nanometer-scale property characterization for techniques such as TEM	Characterize and understand defects
Atomistic models	Apply models developed outside PV R&D context
System-level modeling	None
Transmission-line reflected wave techniques	Measure signature of reflected waves sent down string of modules to identify problems
In-situ microscopy	Study module degradation mechanisms
3D griddler model that includes substrate	Improve contact design
Modeling for contact degradation	Study degradation modes
Open-source molecular modeling software	Software such as Lammps that span length and time scales but were developed outside of PV R&D
X-ray based microscopy and tomography	Characterize defects in realistic operating environments
Kelvin probe and conducting atomic force microscopy	Provide information about microstructure and charge transport, connecting to device performance
Grain boundary models applicable across absorbers	Understand defects and connect to device performance
System- and grid-level machine learning modeling	Apply to understanding of grid topology and resilience

3 Module Packaging and Reliability

3.1 What module packaging components are most critical to improve in order to increase module lifetimes, decrease degradation rates, or minimize O&M costs?

Responses to question 3.1 addressed both critical packaging components to improve as well as the reliability, cost, or other challenges associated with these materials. Figure 9 reports the percent of responses that discussed different module materials or related concepts, whereas Figure 10 reports the percent of responses discussing different technical challenges associated with these materials.

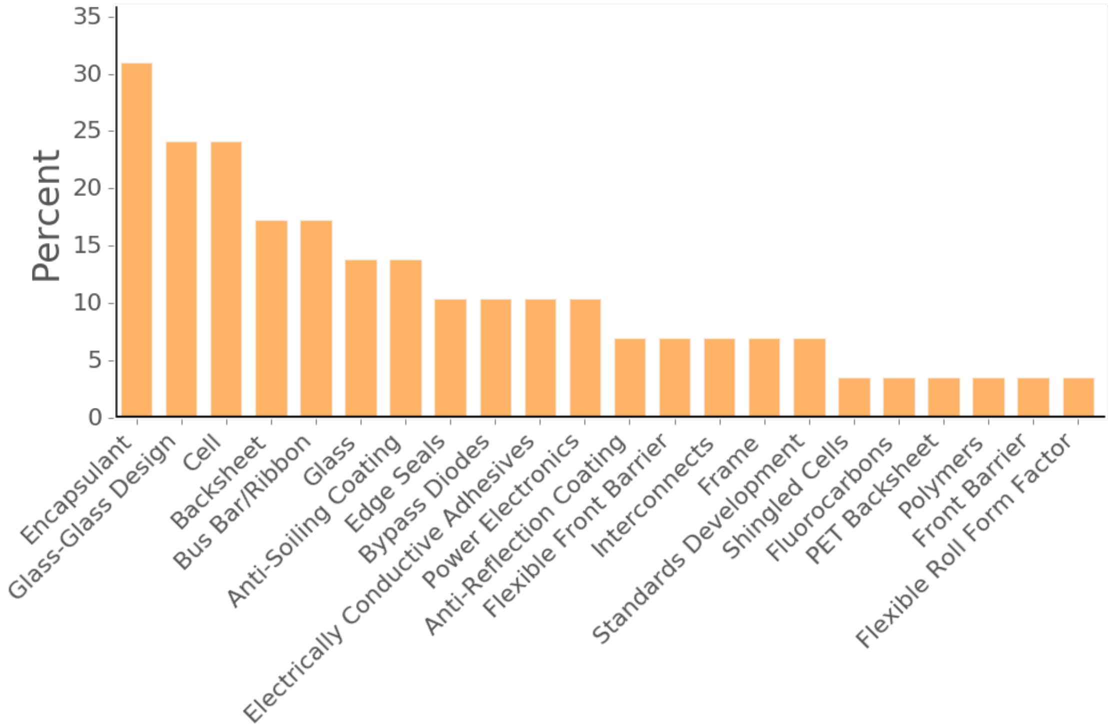

Figure 9. Percent of responses to Question 3.1 that discussed each of the module packaging components listed along the x-axis of the graph.

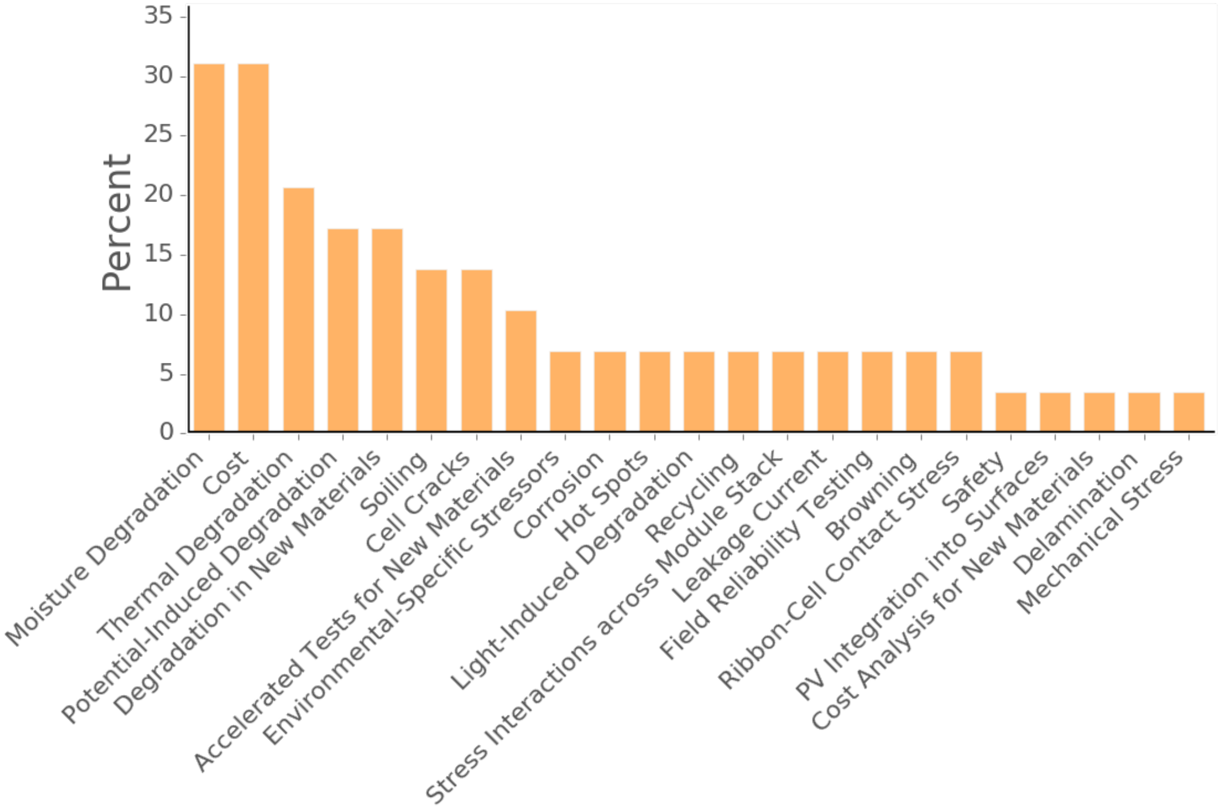

Figure 10. Percent of responses to Question 3.1 including discussion of challenges listed along the x-axis.

Although the above figures provide an overview of the most important materials and challenges, they do not connect which specific issues in Figure 10 are relevant to which materials in Figure 9. Therefore, Table 6 reports the top reported challenges for the five most frequently discussed module materials listed in Figure 9.

Table 6. Most frequently reported challenges for the top five reported module materials critical to increasing module lifetimes and decreasing degradation rates of PV modules.

Module Material	Challenge
Encapsulant	Cost, Moisture Degradation, Potential-Induced Degradation, Degradation in New Materials
Glass-Glass Design	Cost, Cell Cracks
Cell	Cell Cracks, Thermal Degradation, Light-Induced Degradation
Backsheet	Accelerated Testing of New Materials, Cell Cracks, Stress across Module Stack, Cost
Bus Bar / Ribbon	Ribbon-Cell Contact Stress, General Degradation / Failure, Cost

3.2 What are the most important accelerated tests and related performance standards to be developed to improve module and system reliability leading to 30-50 year lifetimes?

Figure 11 shows the most frequent responses related to improved accelerated tests and performance standards necessary for 30-50 year module lifetimes. Due to the heterogeneity of responses, categories listed in Figure 11 range from general types of tests that respondents believe are important (e.g. thermal cycling, bias) to very specific proposals of how to improve accelerated tests (e.g. accelerated tests with in situ characterization).

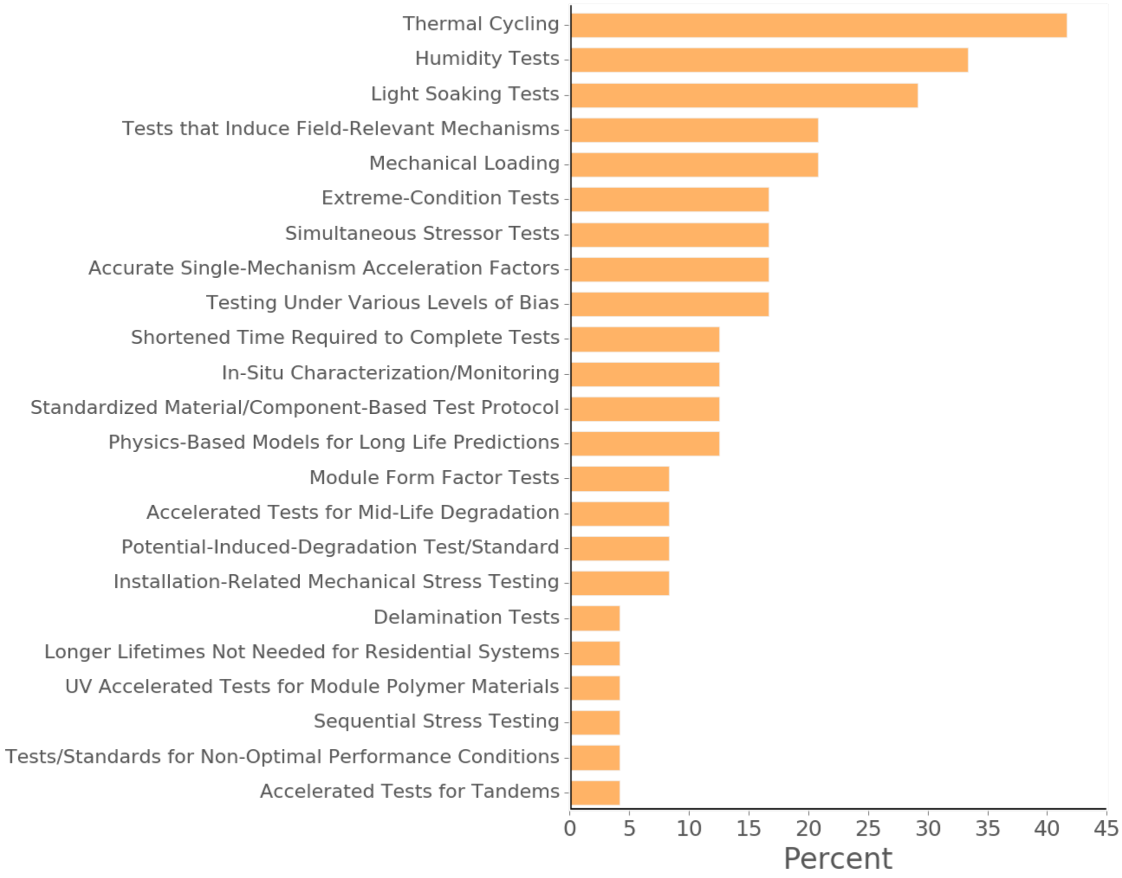

Figure 11. Percent of responses to Question 3.2 that discuss each of the issues about accelerated testing and performance standards listed on the left-hand side of the graph.

3.3 What public data and analytical tools would be most useful to facilitate PV module material and packaging R&D to decrease degradation rates, improve material quality, mitigate financial risk, and/or decrease costs?

Figure 12 lists manually determined categories of data needs and the percent of respondents discussing each category based on RFI responses to Question 3.3. Table 7 reports examples of desired analytics tools to analyze degradation rates, material properties, and financing.

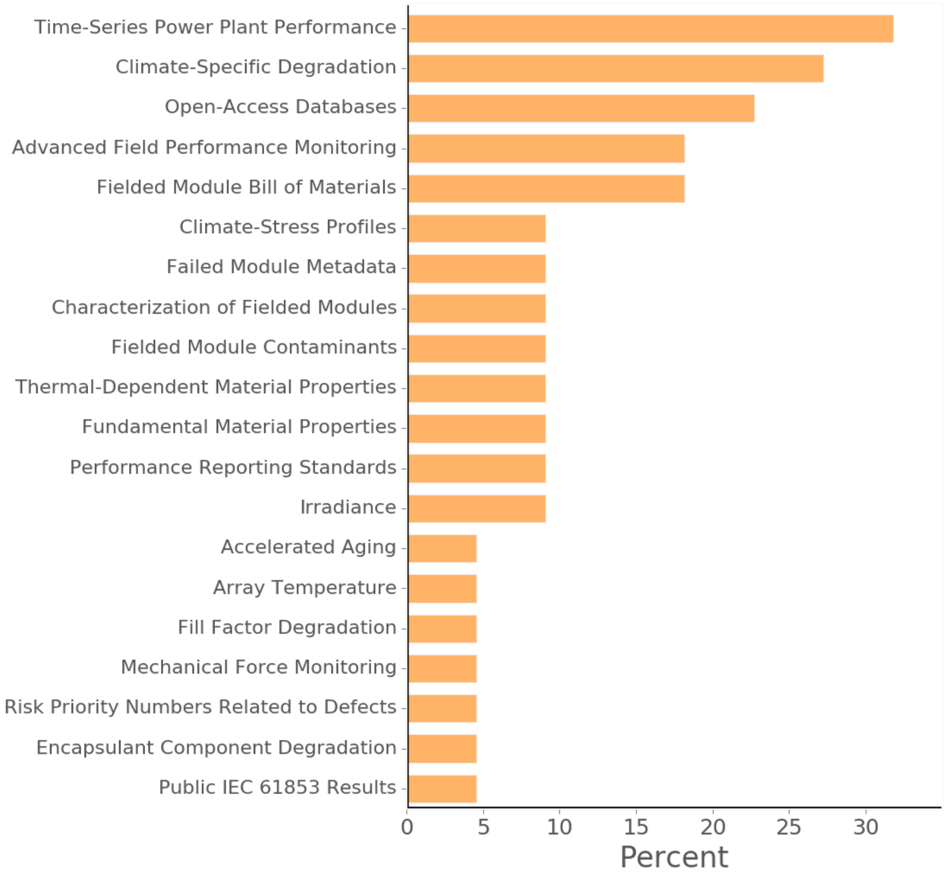

Figure 12. Percent of respondents discussing each of the data needs listed on the left-hand side of the graph in response to Question 3.3.

Table 7. List of primary data analytics needs included in responses to Question 3.3 that would assist with research and development to reduce degradation rates, financial risk, and costs.

Data Analytics Needs
Financial models demonstrating impact of reducing degradation rates
Machine learning tools that diagnose degradation causes using plant performance data
Open-access to analysis tools
Physical models that predict module performance and lifetime
Moisture ingress models
Analyses for competitive benchmarking to reduce financial risk
Education about energy prediction models
Potential-induced degradation models
Finite element analyses of fielded stressors

Oxygen diffusion models
Photothermal degradation model for module materials
Component-level failure models
Automated image processing
API functionality of analysis tools

4 Portfolio Evaluation

4.1 How should SETO PV R&D funding programs measure their success?

Figure 13 shows the most frequently reported categories for how respondents believed SETO could measure success across its PV R&D funding portfolio. Due to the range of responses, categories span from specific metrics, such as publication counts, to general, more qualitative topics such as reporting on improved scientific understanding that comes from funded projects.

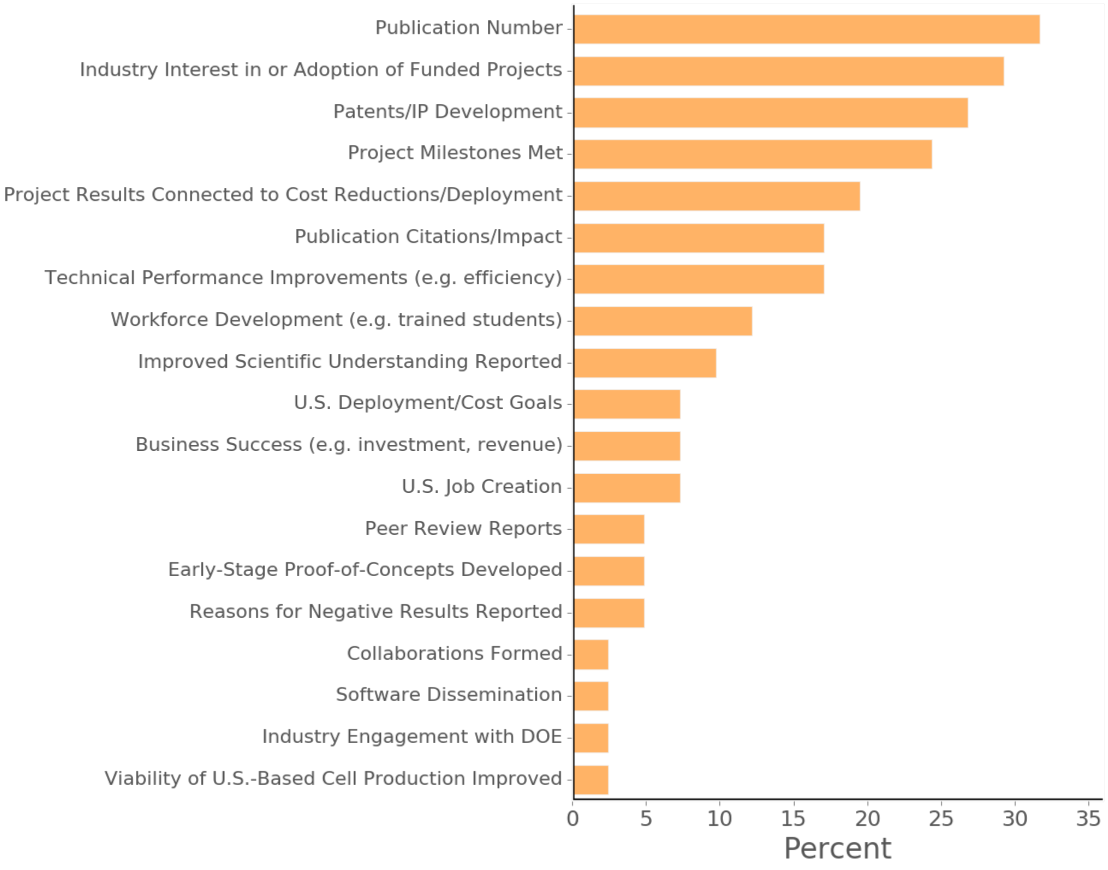

Figure 13. Percent of responses to Question 4.1 that discussed the categories listed on the left-hand side of the graph regarding how to measure the success of SETO PV R&D funding programs.

4.2 How should high-risk, applied research projects be structured to maximize the impact of public funding?

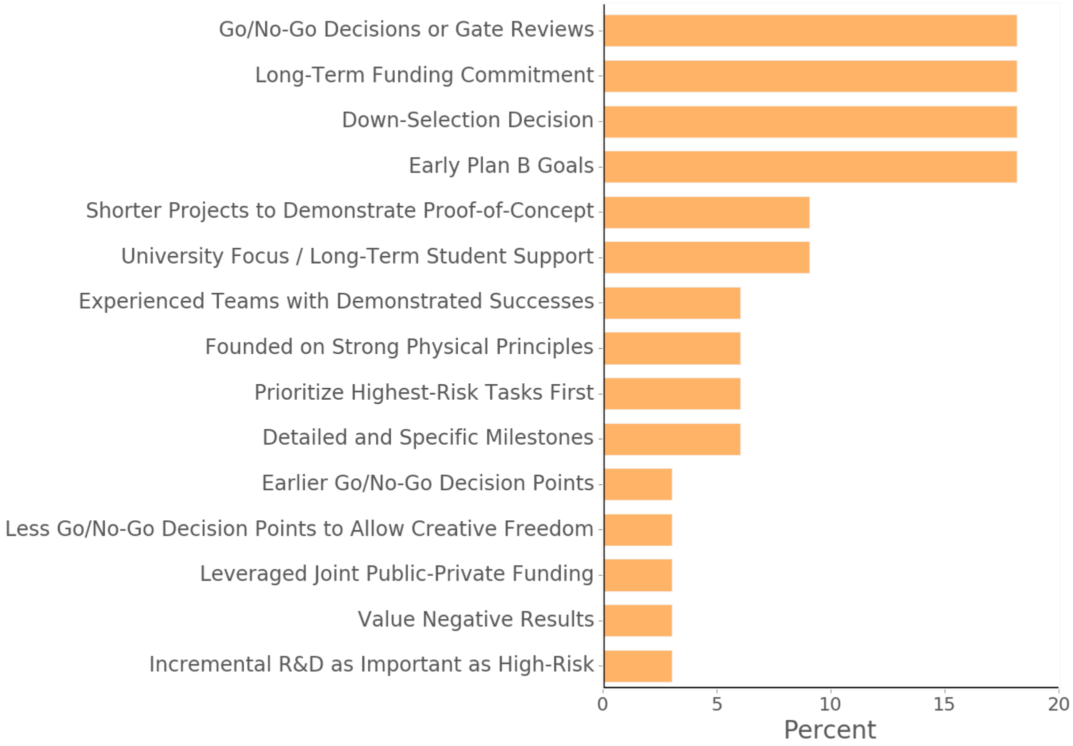

Figure 14. Percent of responses to Question 4.2 discussing each of the categories on the left-hand side of the graph regarding methods to structure high-risk research and development projects.

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