SunShot Modules and Systems Workshop
September 2016, Las Vegas, NV

I. Introduction

DOE's SunShot Initiative held the Modules and Systems Workshop on September 15, 2016 in Las Vegas, Nevada. This workshop facilitated discussion between solar researchers, industry professionals, and other relevant stakeholders with the goal of informing the development of a research agenda focused on Module and System level research. Discussion during the workshop was framed in three main ways: (1) Creating a module-level and systems-level vision and identifying research directions that should be prioritized for federal funding, (2) Establishing metrics to govern research and development in the module and system space, and (3) Identifying barriers that inhibit the performance or viability of current and future PV technologies. Additional discussion was dedicated to the identification of diagnostic, measurement, and analysis capabilities that would offer the most value to the PV industry and research community should new tools or methodologies become available.

The following sections summarize some of the major themes that repeatedly arose during the day. A more detailed list of the topics that appeared during the discussion sessions can be found at the end of the document.

II. Summary of Outcomes for Module-Level Research

The discussion of module-level research directions, metrics, and barriers produced the picture of a national (federal and commercial) R&D framework that was far from complete, but that provided a relatively solid foundation upon which to build future efforts.

One of the primary themes that arose within the module development space was the transition from standard test conditions to fielded performance. Module price in $\$/W_{DC}$ remains the gold-standard in judging the market competitiveness of a given product, but as more advanced module technologies appear, the value of deployed modules is beginning to decouple from solely the $/W price. One of the goals that will likely be carried forward from this event is an effort to transition the discussion towards module energy output from performance under standard testing conditions, and whether federal research can provide improved competitiveness through improved understanding for capabilities such as module-level electronics, conductive backsheets, low voltage modules, shade-tolerance, bifacial operation, and many other new technologies.

Module reliability and durability was another clear theme within the module-level discussions. Interest in these areas is a potentially necessary step in order to continuously ensure module quality during the advent of new power electronics, higher voltage system operation, new encapsulation and packaging materials, and new metallization and interconnection methods. Module-level research has historically had a strong reliability focus, and the increasing diversity of PV module and system products that are appearing as the industry matures will likely require continued attention in this area.

Module production and the scalability of PV manufacturing also appeared in many of the discussions, and some concerns were raised that the large capital investments required to establish manufacturing infrastructure both hurt scalability and created substantial inertia against any attempts to modify or improve the state of the art. Attempts to improve module production will likely need to be accompanied by a careful analysis of its compatibility with the existing supply chain, or by creative ways to incubate and demonstrate the bankability of future production methods without requiring manufacturing facilities to massively update their equipment and procedures beforehand.

III. Summary of Outcomes for System-Level Research

Discussions that focused on the system-level research space revealed significant white space where foundational and non-proprietary work was relatively limited. Methods for automation and improving the ease of system deployment along with system operations, maintenance, monitoring, and bankability were brought up as areas with high potential impact that could benefit from federal R&D efforts.

Ease of installation was a recurring theme during the discussion sessions, and the development of new methods to increase installation and commissioning speeds while maintaining quality, performance, and worker safety were topics of significant interest. Examples included automated installation, partial prefabrication, and the development of integrated or simplified PV products that allow for fast and safe installation with minimal need for specialized worker training. Installation standardization and quality assurance were also discussed, with some emphasis on the development of useful standards and best practices as well as tools to quickly certify rooftop systems as fully functional.

System reliability, monitoring, and diagnostics was another important topic during the workshop. At the system level, the reliability focus was on power electronics, and on improving the lifetime and reliability of inverters (whether module-level, string, or central). The ability to monitor, predict, and anticipate failures for power electronics or modules was also identified as an area with significant potential for commercial product development and for research and development efforts as well. It was suggested that the development of models that could accurately predict system or component failure should be designed from a bankability or financing perspective, and that PV researchers might have an increasingly useful role to play as data specialists that support the accumulation and aggregation of environmental and performance data from PV systems.

An additional topic that arose as a high level theme in the system level discussions was that of residual and terminal system value, and how future research efforts could provide a degree of certainty and confidence about system value whether at the time of decommission or after the first PPA as the decision is being made whether to re-power a system or replace some or all of its components (i.e. modules).

IV. Summary of Discussion Points from the Breakout Sessions

The following table contains a summary of the various points that were discussed during the workshop's breakout sessions. The discussion topics in the left column reflect the questions posed to the various breakout groups.

Topic	Summary of Discussion Points from Workshop Attendees
PV Module Research Directions that are Currently Deserving of Federal Funding	• The capability for rapid manufacturing scale-up based on improving throughput and reducing CapEx • The identification of adjacent or similar supply chains that could be leveraged for the benefit of the PV industry • Physics-based module characterization and the development of advanced predictive capabilities for module service lifetime • Module designs that are optimized for service conditions, not STC. • The implementation of bifacial modules • Educating the finance community regarding differences in module characteristics, behavior, advantages, and disadvantages. Designing modules that are not a commodity • Eliminate vacuum lamination: 13-15 min low tech process vs 30 sec cell processing; laminators are high capex; lamination is not uniform • Eliminate hydrophilic materials in the module that draw in moisture if there a breach in encapsulation leading to increased corrosion • Lead-free metallization that improves reliability (stress-free metallization) • Frameless modules that simplify installation • Improve module packaging and process design to package for reliability • Thermal management in modules and systems • Application-specific modules: residential vs. commercial vs. utility
PV System Research Directions that are Currently Deserving of Federal Funding	• Residual value and terminal value studies. PV recycling and de-commissioning value. Modules and other components can be designed to maximize terminal value • Automating installation: new robots/machines, simpler installation practices that can leapfrog current module architecture and installation practices • Expanding the field of PV research to further emphasize data science and data aggregation, particularly data related to system bankability • User behavior monitoring and constantly acquire voice of the customer-type data on PV system installation and operation • Application-specific design and testing standards (e.g., for qualification of flexible modules). • In-field metrology and diagnostics: Reduce the number of false positives and missed negatives in the detection of systems (especially at inverters level – e.g. ground faults) • Designing and qualifying solar-ready homes • Improving uniformity and standardization of the installation process • Inverter cost, performance, reliability, and functionalities • Automated system shutdown for safety purposes • Increase reliability, performance, and bankability of trackers • Bringing storage and PV professionals together • Develop strategies to take advantage of economies of scale with distributed installations • Systems as Modules: distributed electronics, multifunctional modules • Increased capacity factor with reduced DC to AC conversion losses • High voltage (1500 V or higher) utility scale system operation • Compact and lightweight power electronics • Improving standardization among racking equipment • Research on corrosion of racking materials • Research on connectors failure and corrosion of connectors due to non-compatible components • Move to composite materials (plastic might get brittle over time, but it doesn't corrode) • Need to develop quality control checks at supplier factories and on the field for new materials

Development Targets for PV Modules	• 20% improvement in energy yield (kWh/kW) at reduced cost • Modules that effectively utilize the entire spectrum and reject or pass all non-useful light • Dramatically reduced capex and manufacturing costs for modules • Resilient modules: Tolerant to non-uniformities in performance, cell-level power optimization, self-healing circuits and packaging, degradation resistant • 25% efficiency, $0.25/Watt, 50 year lifetime
Development Targets for PV Systems	• Fail-safe, O&M-free for 30 years • 50% reduction in manual contribution to installation costs • Modeling software for system design, construction and performance over time should be widely available for installers and regulators. • High efficiency systems with low degradation rates • Module and system design for a highly scalable industry • Pre-wired and pre-fabricated systems with modules as big as a parking space • Factory in the field: 24/7 installation, highly automated, emphasize productivity and process efficiency
Potential Module-Level Metrics to Help Guide and Assess Research and Development Progress	• Module Cost ($/W) and Operating Margin (Price minus Cost, $/W) • Percent deviation of module power output from its predicted value every year • Spread in manufactured nameplate efficiency • Energy Density: KWh/kW/m^2 • Module warranty claims per year for each model • Total energy payback over life cycle, including decommissioning/recycling -- • Degradation rate • Shading linearity • Maintenance frequency • Mechanical Durability (shipping survival rates) • Efficiency at NOCT -- • Cost of electricity ($/MWh) • Degradation/Lifetime • Energy yield • Operating temperature • Recyclability -- • Energy Yield • Manufacturing CapEx • Degradation curve (degradation rate as a function of time), including module level electronics and geographically specific degradation rates. • Tolerance of differences between climates, deployment conditions relative to STC / performance under non-ideal conditions. Tailor safety to operating environment. • Cell-to-module gain in power output. -- • Cost ($0.30/W, $0.03/kwh) • Reliability (%degradation/yr, variability among a population) • Energy Yield over 25 years (kWh/m2/yr) at a given insolation level. • Specific Power (W/kg) • Installation Speed (W/person/hr)

Potential System-Level Metrics to Help Guide and Assess Research and Development Progress	• Value of Power (time and location, % of electricity curtailed, maintaining available dispatchable capacity by operating at less than 100% under normal conditions) • CapEx across all system components • Uniformity of system design procedures and system installation quality • Efficiency of O&M (truck rolls per kWh, accuracy/availability of information, the ability to tailor operations and maintenance to geographic location) • Cost of lost time (permitting, interconnection, etc.) and number of revisions to system designs -- • Cohesion of system component lifetime (modules vs. racking vs. electronics, etc.) • Energy yield and value of electricity • Installation Rate (kW/person/hr) • Overall system degradation rate (kWh/m^2/yr during year 1 and year 10). • Lost production area (roof edges, unused land, etc.) -- • Market value of PV generation (Load-matching systems, dispatchability, maximizing value of generation). • Grid support rating (voltage and frequency support). • Levelized cost of energy. • System degradation Rates. • O&M costs. -- • Accuracy of system energy output predictions, certainty of revenue cash flows. • Standard deviation of system failure rates (system failure could be defined at a given % loss in power output). • Installation quality (% yield of constructed systems). • Utilization and efficiency of energy injection into the grid. • Price point for residential PV + storage (e.g, compared to backup generators and grid parity). -- • System cost and levelized avoided cost of electricity • Dispatchability of PV electricity • Reliability of PV systems • Speed to get online from installation through permitting, inspection, interconnection • PV system aesthetics
Module-Level Technology Barriers that Currently Inhibit Industry Growth and Sustainability	• High start-up costs to develop new prototypes/designs in inflexible manufacturing processes • High capex of manufacturing and difficulty of implementing changes to manufacturing • Insufficient Science-based reliability prediction (accelerated testing) • Insufficient In-situ degradation analysis • High module manufacturing costs, including material costs • Risk-aversion of financing community for new concepts and architectures • Insufficient ability to enable Module-level shut down • Thickness and weight of components is too great • Being able to replace components to maintain performance • Lifetimes cannot be determined via qualification testing • Increase cell-to-module gain (encapsulation, light trapping) • Kinetics of defects is unknown as new module designs are developed • Metallization methods could be improved (minimize corrosion, stress on cells) • Variations in cell efficiency make module production significantly more complex (in-line characterization + sorting). Modules that are tolerant to variations in cell efficiency could help get around this.

System-Level Technology Barriers that Currently Inhibit Industry Growth and Sustainability	• Insufficient system self-monitoring • Safety codes to what goes on the roof are vary widely, causing a lot of safety infractions. Need to reduce installation times and improve procedures to reduce safety issues. • Safety PPE is not always convenient and can be challenging for workers • Highly integrated systems are harder to test for bankability (bankability of each individual component is easier). Need to work with testing houses for testing procedures and certifications for integrated systems, achieving bankability at the system level (one test including design, installation, operation, asset management and transfer…). • Better certification tests for individual components and integrated systems will drive changes in the industry and in procedures • Tax incentives are encouraging quick turnaround and energy production in the first year rather than systems with high energy yield over long lifetime. • Barrier to efficient use of generated solar DC electricity prevents energy-independent residences • Perceptions of the negative effects of high penetration solar • Losses associated with AC power transportation • Lack of data on solar electricity usage and generation. Need to enable communication between utility and inverters and between systems • There is insufficient redundancy in system-level wiring and power electronics. • Insufficient system-level data to accurately produce financing rates and other agreements. • Power electronics are bulky, and reliability is uncertain. • System aesthetics could be improved • System contract lifetimes • Inadequate standards for community-scale systems • System maintenance is inefficient and expensive. • BIPV systems are expensive • No market for using system components outside of system performance • O&M costs are perceived as a cost center not a value center
Opportunities for Developing Module-Level Measurement and Diagnostic Capabilities	• Detailed energy loss analysis of modules • Integrated test structures for research – E.g., tagging modules to see how they change during operation • Predict degradation trajectory of a module • Module to module variability • Measuring temperature internally • Develop non-destructive characterization tools to measure defects in module before and during operation • Develop field measurement of EVA degradation (measure absorption characteristic of the encapsulant) • Develop material quality standard to be verified even before entering the manufacturing line, along with quality check through and after production • Functionality testing for bypass diodes • Manufacturing simulations to lower the barrier to try out new process flows and prototypes • Comprehensive testing and simulation methodology to predict module lifetime • Non-destructive characterization tools to measure defects in module before and during operation • Prediction of how (cell) cracking will affect performance • Measure how much EVA has degraded (measure absorption characteristic of the encapsulant) • Map trajectories of impurities and other defects • Differentiate between benign and malignant defects • Environmental monitoring – vegetation control

Opportunities for Developing System-Level Measurement and Diagnostic Capabilities	• Qualifying procedure for installers, e.g., low-cost in-field diagnostic procedure for system performance before and after installation. Procedure for installation certification • Tools related to system fault detection, analysis, and the diagnosis of any failures, degradation, or power loss issues • Production forecasting tools • Remote sensing using little manual labor to reduce O&M costs • Tools for remote system commissioning and remote system inspection • Irradiance-based and physics-based models to predict PV performance under different conditions needs to be established, validated, and then used for financial models. • Data sets dedicated to tracker performance across the US. Tracker qualification tests and lifetime tests. • Field inspection tools: fielded IR imaging, fielded EL imaging, fielded EQE • Automated system diagnostic methods (e.g., drones instead of manual inspection, smart inverters able to measure and transmit I-V curves, inverters that monitor their own operating temperature) • Develop live, automated system to compare performance of your system with your neighbor to detect inverter/system failures as soon as they happen